

19. CHEMICAL VARIANCE IN DEEP OCEAN BASALTS

Roger Hart, Physical Research Laboratory, Ahmedabad 380009, India

ABSTRACT

Multiple regression analysis was used to determine the relative importance of crystal fractionation, partial melting, and seawater alteration on the concentrations of 28 elements in deep ocean basalt. The components Al_2O_3 , P_2O_5 , and H_2O were used as independent variables to represent each of these processes, and the computer-derived equations show a high level of significance for all 28 elements.

The Al_2O_3 , total Fe, and TiO_2 of oceanic basalt vary greatly in any given region of the oceanic crust due to small-scale crystal settling. The oceanic crust is enriched in large-ion-lithophile (LIL) elements with time by off-ridge volcanism. With the notable exception of Zr and Hf, seawater alteration probably affects the concentration of LIL elements, but much less than partial melting. Seawater alteration leaches significant amounts of Si and Ca from oceanic basalt while enriching it in K, Li, and B.

INTRODUCTION

The study of chemical variation in deep ocean basalts provides a unique opportunity to evaluate the chemical characteristics of the upper mantle and the magmatic processes which generate the oceanic crust at spreading centers. However, secondary chemical exchange between oceanic basalt and seawater produces an overprinting which obscures the primary relationships. Furthermore, off-ridge volcanism contributes a component to the oceanic crust which is unlike that formed at ridge crests. The purpose of this paper is to establish criteria which will help in distinguishing chemical relationships produced by magmatism at ridge crests from those produced as an overprint by chemical exchange with seawater and those contributed by off-ridge volcanism.

Covariant and multivariate analyses were applied to all chemical data available on basement rocks cored on the first 29 DSDP legs. The analyzed DSDP samples include, in addition to tholeiitic pillow lavas, differentiated andesitic basalts, alkali and transitional-type basalts, and basalts rich in olivine and pyroxene. Most DSDP basalts are altered to a phyllosilicate assemblage dominated by K-rich smectite. A few samples are metamorphosed to spilite and amphibolite. Sites drilled on spreading ridges or abyssal plains encountered tholeiitic lava flows either fresh, or altered to a smectite-rich assemblage. The unusual rock types and alteration assemblages were encountered mainly in regions thought to be typical sites of off-ridge volcanism such as seamounts, aseismic ridges, and plateaus.

A group of 59 DSDP samples was selected to represent oceanic crust tholeiitic flows typical of ridge flanks and abyssal regions. Hereafter, the group will be referred to as TOPS (Typical Oceanic Profile Samples).

In this work the DSDP data are considered as a whole including the TOPS group. Because of the diversity of

the non-TOPS DSDP samples, they were not considered as a group; however, for the most part, such a group would represent products of off-ridge volcanism. Because of the difficulty of distinguishing sills from flows, there is no way of knowing for sure if the TOPS basalt contains samples produced by off-ridge volcanism, but an effort has been made to eliminate the most obvious cases.

The elemental abundance relations in all DSDP basement samples and TOPS group of DSDP samples have been compared to Mean Ocean Ridge Basalt (MORB). The chemical data on DSDP volcanic rocks are taken from the Initial Reports of the Deep Sea Drilling Project and was compiled by Vallier (1974). The literature sources for the ridge basalt defining MORB are given in Appendix A along with specific references on the DSDP volcanic rocks.

This paper is divided into three sections. The first section compares the chemical composition of MORB with the average chemical composition of all DSDP basement samples and TOPS group of DSDP samples. The second section presents the results of a study of covariant element abundance ratios and multiple regression analysis of all three groups of basalts undertaken to establish the relative importance of magmatic processes and seawater alteration processes in determining the concentrations of various elements in the oceanic crust. The third section reports on the variation of elemental concentrations with age of the oceanic crust and depth of drill penetration into the basement.

COMPARISON OF THE AVERAGE COMPOSITION OF ALL DSDP BASEMENT SAMPLES WITH TOPS BASALT AND MORB

The average chemical compositions of all DSDP basement samples, TOPS basalt, and MORB are given in Table 1 (major elements) and Table 2 (trace elements).

The means and standard deviations are quite distinct in all three of these groups for a number of elements. The chemical variability is highest for all DSDP basement samples. TOPS basalts show higher variability than

MORB. The major and trace elements have been classified in Table 3 (for major elements) and Table 4 (for trace elements) according to an intergroup comparison of their means and standard deviations. Figures

TABLE 1
Comparison of the Major Element Chemistry of Mean Ocean Ridge Basalt (MORB)
and Typical Oceanic Profile Samples (TOPS) with all DSDP Basement Samples

	Mean Ocean Ridge Basalt (MORB)			Typical Oceanic Profile Sample (TOPS)			All DSDP Basement Samples		
	Mean	Standard Deviation	No. of Samples	Mean	Standard Deviation	No. of Samples	Mean	Standard Deviation	No. of Samples
SiO ₂	49.92	0.61	49	49.09	1.54	59	47.85	3.28	157
Al ₂ O ₃	16.08	1.41	49	15.48	1.39	59	15.33	1.40	157
TiO ₂	1.46	0.31	49	1.55	0.69	59	1.67	0.83	157
Total Fe as Fe ₂ O ₃	10.29	1.43	49	10.48	2.08	59	10.86	2.13	157
MgO	7.75	0.77	49	6.72	1.45	59	6.57	1.82	157
CaO	11.21	0.63	49	10.66	2.14	59	9.55	2.33	157
Na ₂ O	2.79	0.26	49	2.73	0.58	59	2.85	0.71	157
K ₂ O	0.17	0.06	49	0.49	0.68	59	0.87	0.92	157
H ₂ O	0.77	0.29	49	2.65	1.31	59	3.71	2.19	157
MnO	0.17	0.03	45	0.18	0.06	45	0.17	0.06	98
P ₂ O ₅	0.15	0.05	42	0.18	0.11	50	0.27	0.23	139
Fe ₂ O ₃	1.49	0.50	42	3.77	1.81	42	4.99	5.53	128
FeO	8.04	1.26	42	5.96	2.27	42	5.74	2.14	128
Fe ₂ O ₃ /FeO	0.19	0.08	42	0.92	0.90	42	1.04	0.81	128

TABLE 2
Comparison of the Minor Element Chemistry of Mean Ocean Ridge Basalts (MORB)
and Typical Oceanic Profile Samples (TOPS) with all DSDP Basement Samples (in ppm)

	Mean Ocean Ridge Basalt (MORB)			Typical Oceanic Profile Sample (TOPS)			All DSDP Basement Sample		
	Mean	Standard Deviation	No. of Samples	Mean	Standard Deviation	No. of Samples	Mean	Standard Deviation	No. of Samples
B	ND ^a	ND	ND	ND	ND	ND	17.52	43.26	21
Ba	25.40	27.02	20	63.00	118.06	35	126.11	203.32	81
Cl	ND	ND	ND	87.50	123.26	6	377.30	280.29	23
Co	43.75	14.62	16	46.44	13.10	9	49.72	13.87	40
Cr	291.29	98.32	16	260.09	105.98	32	223.88	130.67	77
Cu	79.80	29.30	16	56.19	32.89	27	70.78	50.16	65
Eu	1.03	0.21	5	1.03	0.49	8	1.25	1.13	14
Ga	23.75	11.56	16	25.04	10.47	24	26.90	31.87	58
Hf	ND	ND	ND	2.63	1.61	6	2.44	1.32	9
La	3.02	1.01	6	ND	ND	ND	4.93	4.53	5
Li	5.44	1.87	9	9.81	3.54	16	15.87	14.10	24
Mo	ND	ND	ND	0.41	0.22	7	1.15	1.44	12
Nb	ND	ND	ND	2.84	5.83	13	14.57	21.48	39
Ni	123.33	39.95	21	128.24	45.68	25	107.32	64.48	63
Rb	1.94	1.68	9	5.44	12.81	11	12.83	22.27	39
Pb	ND	ND	ND	1.08	0.60	7	1.16	0.68	12
S	ND	ND	ND	128.31	230.27	16	124.62	180.86	34
Sc	51.75	17.69	12	40.60	15.09	5	46.80	17.82	15
Sr	121.81	26.06	21	445.64	116.70	33	264.47	234.41	89
Th	ND	ND	ND	0.21	0.21	5	1.42	1.85	14
U	0.28	0.08	6	0.35	0.32	9	0.42	0.39	25
V	286.00	74.52	16	316.42	72.00	24	296.43	132.74	61
Y	38.60	13.46	10	38.89	17.02	30	38.53	28.84	82
Yb	3.75	1.55	12	ND	ND	ND	3.01	1.50	15
Zn	91.81	33.13	16	101.38	36.34	16	97.92	31.33	28
Zr	105.50	38.71	16	113.49	56.95	36	140.91	86.45	93

^aND = No data available.

TABLE 3
Classification of Major Elements According to a Comparison
of Their Means and Standard Deviations in all DSDP Basement
Samples Relative to MORB

Same Mean and Standard Deviation	Higher Mean, Larger Standard Deviation	Smaller Mean, Larger Standard Deviation
Al_2O_3	K_2O	SiO_2
Total Fe	H_2O	MgO
as Fe_2O_3	TiO_2	CaO
MnO	Na_2O	
	P_2O_5	

1 and 2 give means and standard deviations of concentrations in all DSDP basement samples compared to TOPS basalts.

The elements Al, Fe, and Mn show no significant variation among all DSDP basement samples, TOPS basalt, and MORB. A slight decrease in Al and corresponding increase in Fe, Mn, in all DSDP basement samples and TOPS basalts may be indicated. All DSDP basement samples and TOPS basalts are depleted in Ni and Cr while enriched in Co, V, and Ga relative to MORB, suggesting old oceanic crust is more fractionated with respect to olivine than the crust at oceanic ridges.

All DSDP basement samples are enriched in K_2O , Na_2O , P_2O_5 , and TiO_2 as well as the LIL elements relative to MORB. Such enrichment is expected because the DSDP samples include many rocks produced by off-ridge volcanism supposedly involving lower degrees of partial melting than that normally operative at the ridge crest.

The TOPS basalts show LIL-element enrichment relative to MORB although to a lesser degree than all DSDP basement samples. The TOPS basalts contain only tholeiitic flows from ridge flanks or abyssal regions; therefore, the enrichment of LIL elements in TOPS basalts by off-ridge volcanism is not a foregone conclusion. In all, four explanations are possible:

- 1) TOPS basalts contain sills intruded off-ridge.
- 2) TOPS basalts have been LIL enriched by seawater alteration.
- 3) TOPS basalts are enriched in LIL elements relative to MORB because the ridge sources of magma has become depleted in LIL elements as a function of time.
- 4) TOPS basalts have been sampled in regions of LIL enrichment due to changes of ridge spreading rate, influence of mantle plume activity, or underlying mantle inhomogeneity.

An effort to evaluate these four possibilities will be made in the sections that follow. First of all, the covariant elemental abundance relations are examined to determine which elements behave as coherent groups typical of magmatic processes at the ridge crest (as exhibited in MORB), which behave as coherent groups uniquely in off-ridge sites, and which behave as coherent groups correlated to alteration parameters such as H_2O , $\text{Fe}_2\text{O}_3/\text{FeO}$, sonic velocity, and density.

ELEMENT ABUNDANCE RELATIONS

The correlation matrices for covariant relations between site characteristics, physical properties, major elements, and minor elements are given separately in Appendix B for each of the three groups of samples, namely, all DSDP basement samples, TOPS basalt, and

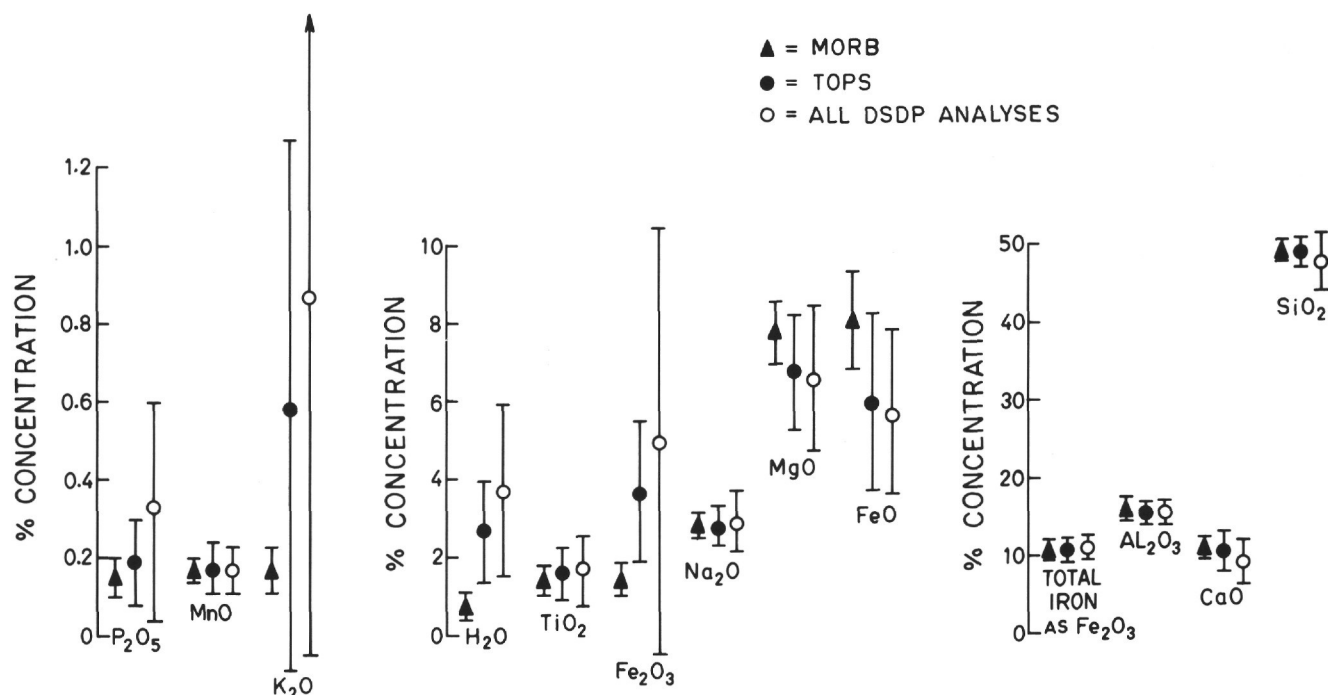


Figure 1. Means and standard deviations of major element concentrations in all DSDP basement samples (open circle) compared to TOPS basalt (closed circle) and MORB (triangle).

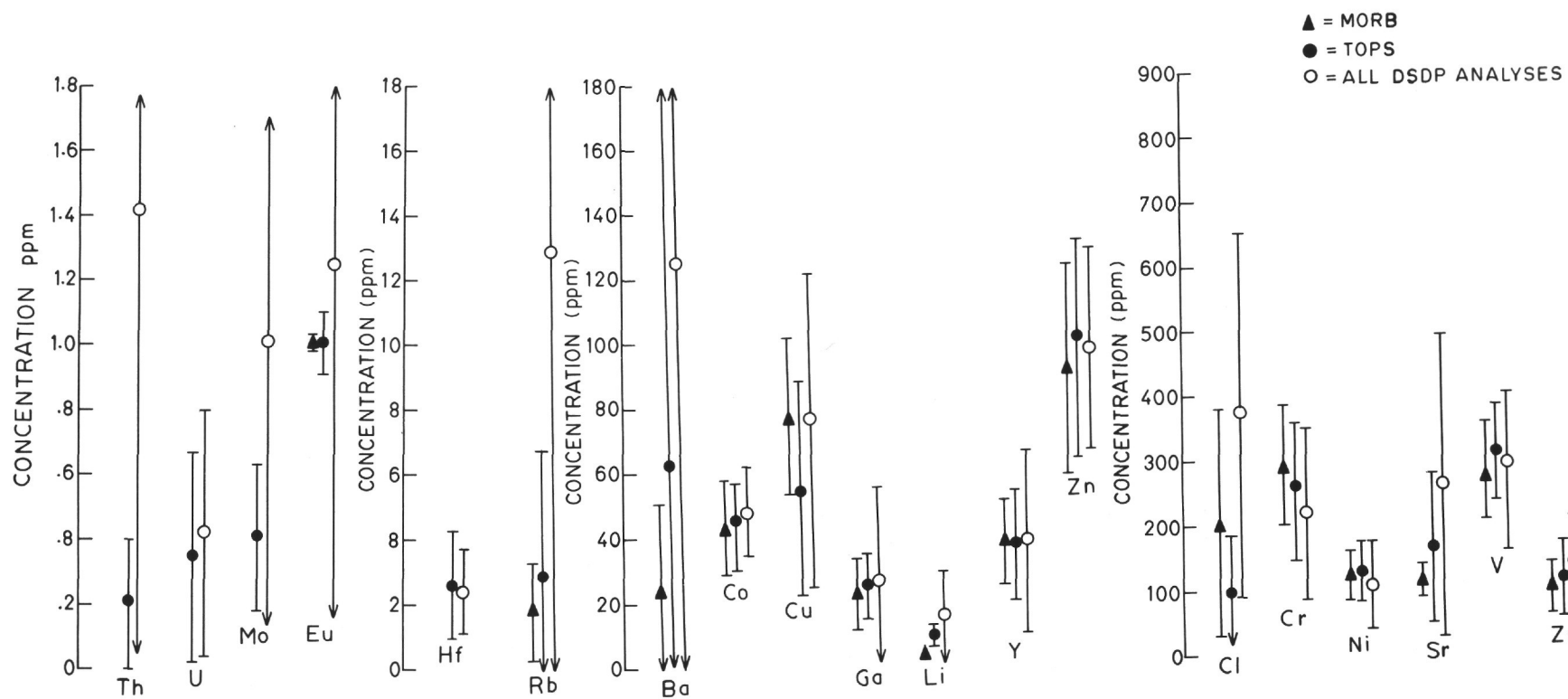


Figure 2. Means and standard deviations of trace element concentrations in all DSDP basement samples (open circle) compared to TOPS basalt (closed circle) and MORB (triangle).

TABLE 4
Classification of Trace Elements According to Comparison
of Their Means and Standard Deviations in all DSDP Basement
Samples Relative to MORB

Similar Mean Larger Standard Deviation	Slightly Lower Mean Larger Standard Deviation	Slightly Higher Mean Larger Standard Deviation	Higher Mean Larger Standard Deviation
Y Cu Zn	Ni Cr	Co V Ga Zr	Th U Mo Nb Rb Ba Li Cl Sr

MORB. The most significant covariant relations are discussed in this section. The major element covariant relations for all DSDP basement samples as represented diagrammatically in Figure 3 provide a good starting point for the discussion. The covariant relations showing the highest degree of correlation can be separated into three groups:

1) Those correlating with the strong negative Al_2O_3 -total Fe covariance shown in Figure 4. The group of covariant relations is thought to be produced by crystal fractionation of plagioclase relative to pyroxene. The covariance of TiO_2 with total Fe and Al_2O_3 is shown in Figure 5.

2) Those correlating with a two to seven time enrichment of LIL elements in all DSDP basement samples relative to MORB. This group is believed to have been produced by small degrees of partial melting of late magmatic phases. Covariant relations involving P_2O_5 are typical of this group. The plot of P_2O_5 versus TiO_2 is shown in Figure 6. All DSDP basement samples containing greater than 0.44% P_2O_5 have been clearly associated with sites of off-ridge volcanism in the DSDP site summaries. Na_2O , MgO , and K_2O also correlate with the group as do the LIL elements Sr, Zr, Ba, and Nb. Some of the best covariant relations in this group are shown in Figures 7, 8, and 9. The lack of correlation between P_2O_5 and H_2O , and P_2O_5 and Al_2O_3 as shown in Figure 10 suggests that seawater alteration and crystal settling of plagioclase relative to pyroxene have not played significant roles in establishing the covariant relationships of this group.

3) Those correlating with parameters of seawater alteration. CaO , SiO_2 , and K_2O show correlation with H_2O and $\text{Fe}_2\text{O}_3/\text{FeO}$ and some of the major covariant relations in this group are shown in Figures 11 and 12.

The degree to which elemental species correlate with each of these groups cannot be specified with a high degree of certainty using only covariant analysis since any given element may relate to more than one, or perhaps all three groups. For this reason a multiple regression analysis was applied to all DSDP basement samples along with the samples defining MORB.

On the basis of their lack of covariance to one another (see Figure 10), Al_2O_3 , P_2O_5 , and H_2O were chosen as independent variables to represent, respectively, fractionation of plagioclase relative to pyroxene, par-

tial melting of late magmatic phases, and seawater alteration. The multiple regression analysis was used to classify 28 elements according to which independent variable they each show the primary correlation. The results are given in Table 5 for those elements correlating primarily with Al_2O_3 , in Table 6 for those elements correlating primarily with P_2O_5 , and in Table 7 for those elements correlating primarily with H_2O . The equations represented in these tables show significant degrees of correlation for all 28 elements and on this basis it seems possible to ascertain much of the history of an oceanic basalt by simply measuring Al_2O_3 , P_2O_5 , and H_2O .

The results of the multiple regression analysis are summarized in Table 8, where the elements are classified according to primary, secondary, or lack of correlation with Al_2O_3 , P_2O_5 , and H_2O .

The elements which show primary correlation with Al_2O_3 are Fe, Ti, Mn, Co, Sc, Pb, Ga, Mo, and Zn. The elements in this group which show no correlation with H_2O are Al, Fe, Ti, Sc. At any given sample location, including mid-ocean ridges, the concentration of these elements may vary considerably because of localized crystal fractionation in small magma bodies.

The elements which correlate primarily with P_2O_5 are the LIL elements Zr, Hf, Ba, Cl, Sr, Eu, Th, U, Rb, and Nb. The major elements Na, K, and Ti correlate positively with P_2O_5 , while Mg, Cr, and Ni show negative correlation. The elements in this group showing no correlation with H_2O are Ti, Zr, and Hf. All other elements in this group may be affected by seawater alteration, but the magnitude of the alteration effect is almost negligible compared to that produced by partial melting.

The elements that correlate primarily with H_2O are Ca, Si, K, Li, Cl, and B. Small secondary correlations are shown by Na, Mn, Ba, Rb, Pb, Sr, Mg, Yb, Eu, Zn, Th, U, Ga, Nb, Cr, Cu, and Nb. The elements showing no correlation with H_2O and therefore the best indications of magmatic processes in the oceanic crust are Zr, Ti, Co, Ni, V, Hf, Sc, Al, and Fe.

The general conclusion of the study of elemental abundance relations in this section is that seawater alteration has not produced the LIL enrichment of TOPS basalt. The next section examines age-dependent elemental relations in the oceanic crust.

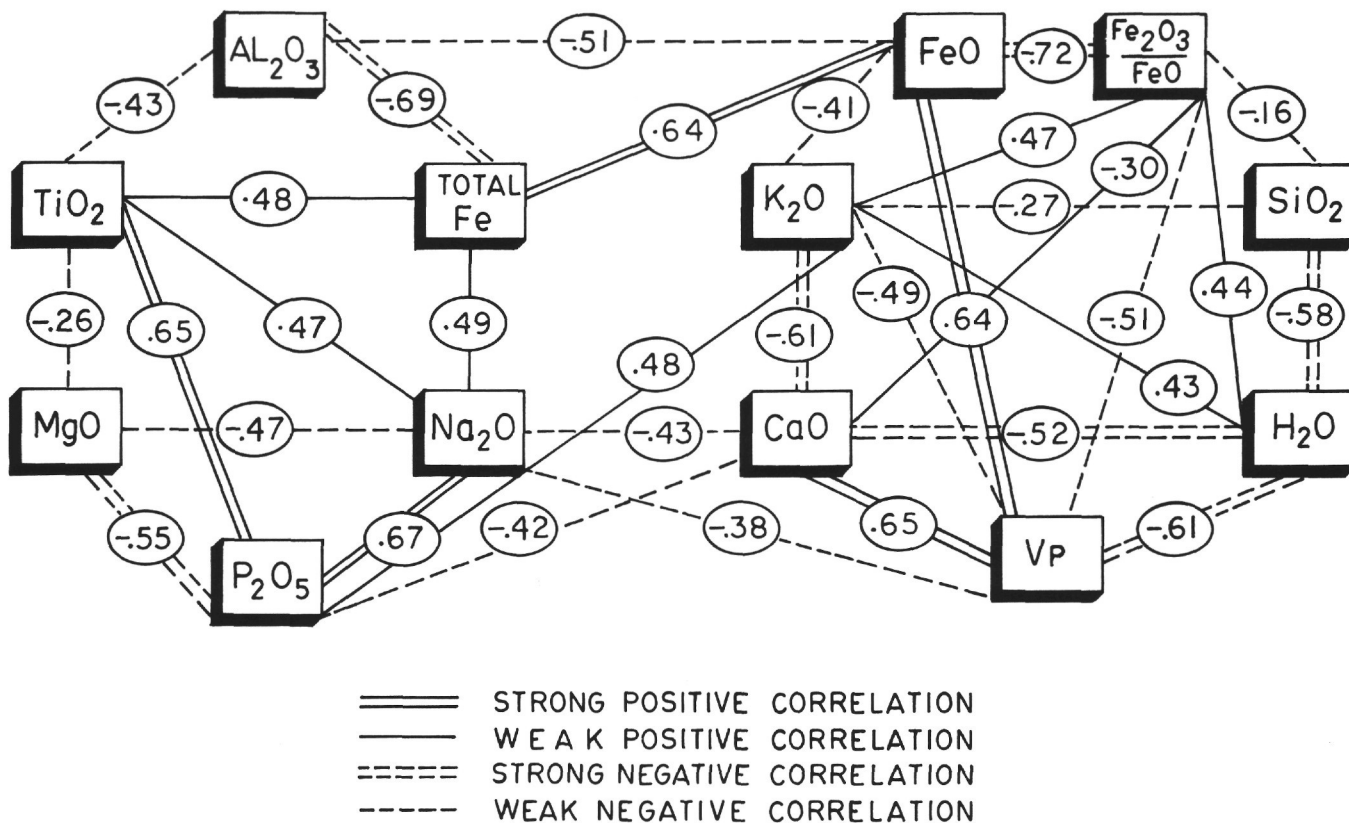


Figure 3. Diagrammatic representation of covariant major element relations in all DSDP basement samples. The numbers in circles are the correlation coefficient, R .

DISCUSSION

Although the average Al_2O_3 and total Fe contents of all DSDP basement samples are similar to MORB, basalts from about 35 DSDP sites have higher total Fe and TiO_2 contents than MORB (see Figures 4 and 5). Only three DSDP basalts have lower total Fe and TiO_2 than MORB. The majority of the high Fe and Ti (FeTi) DSDP basalts are rich in pyroxene, olivine, or chlorite and were sampled from sites of suspected off-ridge volcanism or mantle plume activity such as the Ninetyeast Ridge.

A significant number of TOPS basalts also show FeTi characteristics. FeTi TOPS basalts were encountered at DSDP Sites 61, 159, 160, 161, 166, 169, 172, 256, 261, 319, 320, and 321 which are removed from areas of known off-ridge volcanism or mantle plume activity. In general, the FeTi TOPS sites fall between Latitudes 10°S and 32°N in the Pacific Ocean with two sites (256 and 261) in the same latitude belt in the eastern Indian Ocean.

A possible explanation of FeTi TOPS basalts is that they are sills introduced near the basement-sediment contact. If this interpretation is correct then it appears that the Pacific basin may have been subjected to a higher degree of off-ridge sill intrusion than other ocean basins.

CONCLUSION

The average chemical composition of all DSDP basement sites shows an enrichment in K_2O , Na_2O , P_2O_5 ,

and TiO_2 and a depletion of SiO_2 , MgO , and CaO relative to MORB. The LIL elements Th, U, Nb, Rb, Ba, and Sr are also enriched. The average composition of a group of selected DSDP samples (TOPS) containing only tholeiitic lava flows, either fresh or altered to smectite-rich clay, and samples from only the flanks of spreading ridges or abyssal regions shows a similar but less-pronounced difference in chemical composition relative to MORB.

A multiple regression analysis of the dependency of 28 elements on the Al_2O_3 , P_2O_5 , and H_2O contents of oceanic basalts shows a high degree of correlation for all elements studied and enables an evaluation of the relative importance of crystal fractionation of plagioclase relative to pyroxene, partial melting of late magmatic phases, and seawater alteration in determining the abundance of these element in oceanic basalt.

Crystal fractionation is marked by a coherent negative correlation between Al and FeTi. Elements that substitute for Al or Fe such as Mn, Zn, Sc, Co, and Ga follow this trend.

Small degrees of partial melting of late magmatic stages lead to enrichment of the LIL elements. The elements Ba, Zr, Nb, U, Th, Hf, and P may be enriched by off-ridge volcanism two to seven times the concentrations in MORB. Crystal settling of plagioclase in magma bodies and seawater alteration affect the LIL elements to a much smaller degree than partial melting and therefore basalts with concentrations of LIL (two to

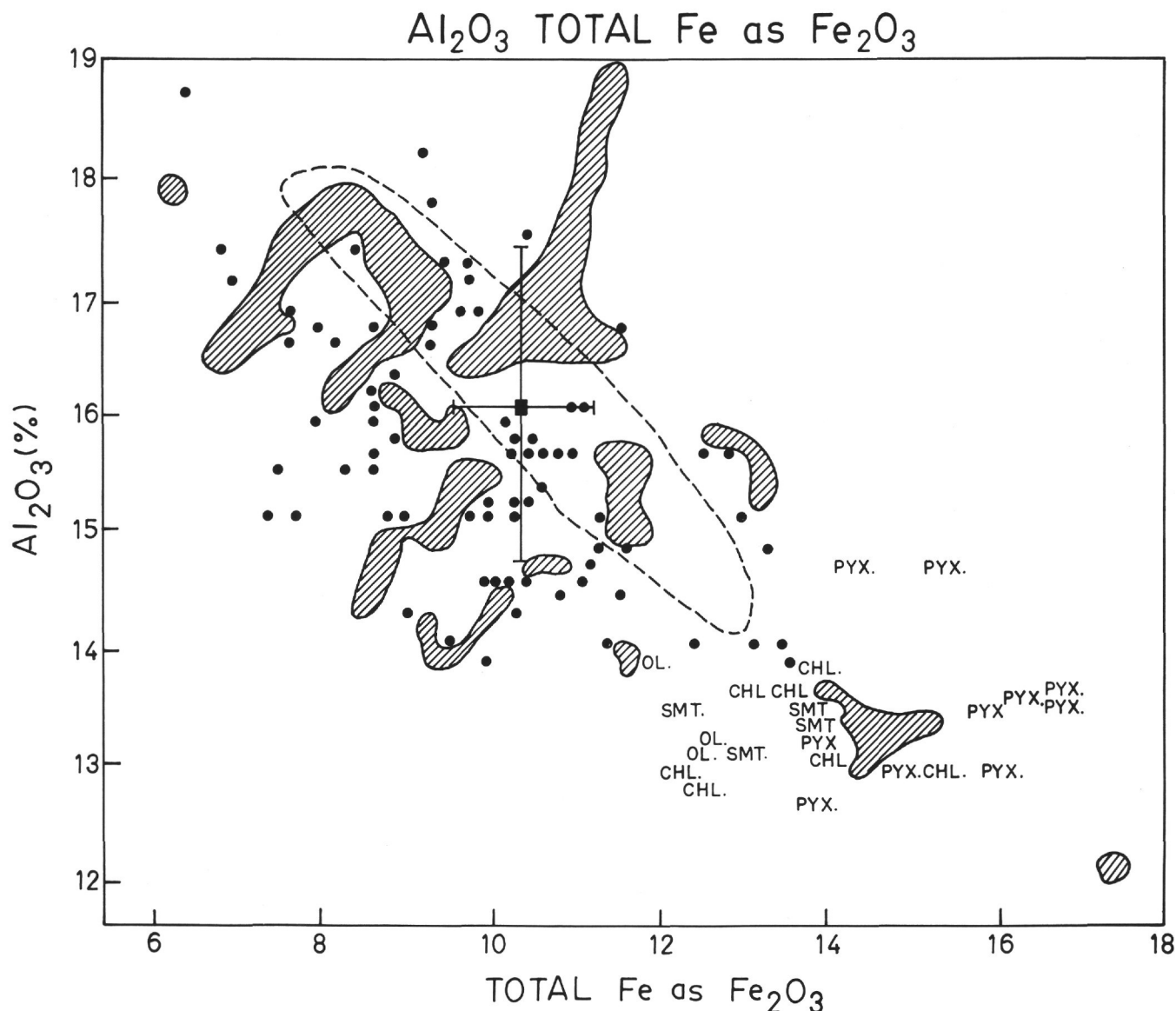


Figure 4. Plot of Al_2O_3 versus total Fe as Fe_2O_3 thought to have been produced by fractionation of plagioclase relative to pyroxene. The means and standard deviations for MORB are indicated by the cross. The dashed line outlines the MORB field. The shaded areas enclose TOPS samples. The dots represent DSDP basement samples not classified as TOPS basalt. PYX = pyroxene-rich sample, OL = olivine-rich samples, CHL = chlorite-rich samples, SMT = alkali basalts from seamounts.

seven times that of MORB) can be safely specified as products of off-ridge volcanism. The origin of basalts with less than two times enrichment of LIL elements can only be judged with knowledge of Al_2O_3 , and H_2O contents. Seawater alteration strongly controls Si, Ca, Li, K, Cl, and B contents of oceanic basalts.

A multiple regression analysis of the dependency of elements in TOPS basalt and MORB on the age of the oceanic crust and depth of drill penetration suggests that the abyssal portions of the oceanic crust are systematically enriched in Na_2O , P_2O_5 , and TiO_2 by continuous intrusion of basalt at the basement-sediment interface. Abyssal high titanium (FeTi) basalts appear to be most common in the equatorial Pacific and eastern Indian Ocean suggesting that these regions may be more subject to interplate volcanism than other oceanic regions.

ACKNOWLEDGMENTS

A critical reading by M.N. Bass inspired extensive revision of this manuscript. However, the author takes full responsibilities for the ideas presented. A grant from the Carnegie Institute of Washington made the author's participation of Leg 34 possible. The Physical Research Laboratory supported the author's shore-based computer studies. The author feels grateful to the sailors, roughnecks, and technicians aboard *Glomar Challenger* who made the collection of samples in this study possible.

REFERENCES

- Aumento, F., 1968. The Mid-Atlantic Ridge near 45° N. II: Basalts from the area of Confederation Peak: *Canadian J. Earth Sci.*, v. 5, p. 1-21.
- Bass, M.N., Moberly, R., Rhodes, J.M., Shih, C.X., and Church, S.E., 1973. Volcanic rocks cored in the Central

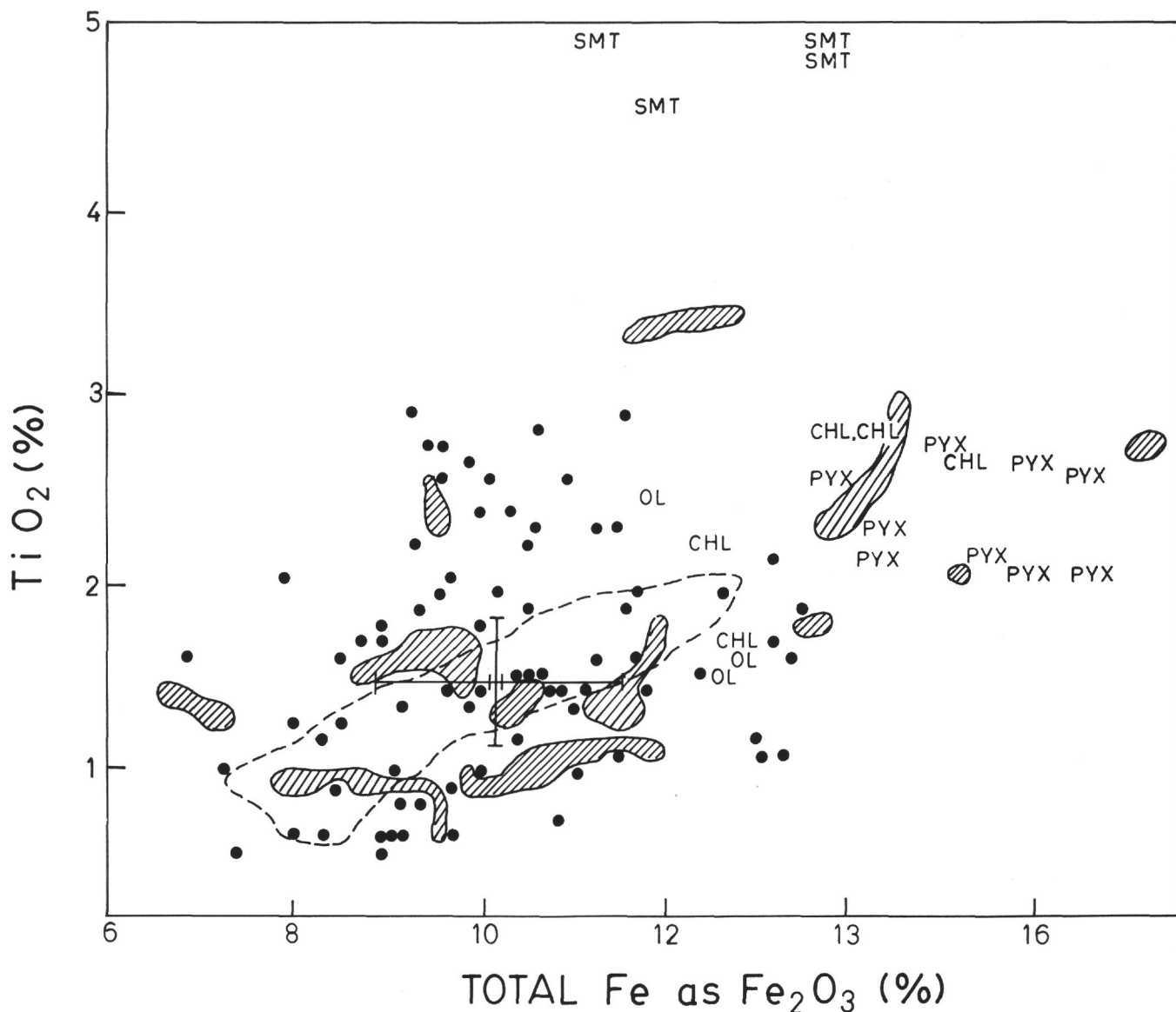


Figure 5. Covariant relations in the Al-FeTi group. The crosses represent the means and standard deviations of MORB. The dashed lines enclose the MORB field. The shaded areas enclose TOPS samples. The dots represent DSDP basement samples not classified as TOPS basalt. PYX = pyroxene-rich samples, OL = olivine-rich samples, CHL = chlorite-rich samples.

- Pacific, Leg 17, Deep Sea Drilling Project. In Winterer, E.L., Ewing, J.I., et al., Initial Reports of the Deep Sea Drilling Project, Volume 17: Washington (U.S. Government Printing Office), p. 429-504.
- Coleman, R.G., 1974. Petrology of igneous rocks in the site chapters. In Whitmarsh, R.B., Weser, O.E., Ross, D.A., et al., Initial Reports of the Deep Sea Drilling Project, Volume 23: Washington (U.S. Government Printing Office), p. 813-820.
- Donnelly, T.W., Melson, W., Kay, R., and Rogers, J.J.W., 1973. Basalts and dolerites of Late Cretaceous age from the central Caribbean. In Edgar, N.T., Saunders, J.B., et al., Initial Reports of the Deep Sea Drilling Project, Volume 15: Washington (U.S. Government Printing Office), p. 989-1011.
- Engel, A.E.J., Engel, C.G., and Havens, R.G., 1965. Chemical characteristics of oceanic basalts and the upper mantle: Geol. Soc. Am. Bull., v. 76, p. 719-734.
- Erlank, A.J. and Reid, D.L., 1974. Geochemistry, mineralogy and petrology of basalts, Leg 25, Deep Sea Drilling Project. In Simpson, E.S.W., Schlich, R., et al., Initial Reports of the Deep Sea Drilling Project, Volume 25: Washington (U.S. Government Printing Office), p.
- Hart, R.A., 1970. Chemical exchange between sea water and deep ocean basalts: Earth Planet. Sci. Lett., 9, p. 269.
- Hart, S.R., Erlank, A.J., Kable, E.S.D., 1974. Sea floor basalt alteration: Some chemical and Sr isotopic effects: Preprint.
- Hekinian, R., 1971. Chemical and mineralogical differences between abyssal hill basalts and ridge tholeiites in the eastern Pacific Ocean: Marina Geol., v. II, p. 77-91.
- , 1973. Petrology of igneous rocks from Leg 22 in the northeastern Indian Ocean. In voh der Borch, C.C., Sclater, J.G., et al., Initial Reports of the Deep Sea Drilling Project, Volume 22: Washington (U.S. Government Printing Office), p. 413-448.
- Honnorez, J. and Fox, P.J., 1973. Petrography of the Gorringer Bank "Basement". In Ryan, W.B.F., Hsü, K.J., et al., Initial Reports of the Deep Sea Drilling Project, Volume 13: Washington (U.S. Government Printing Office), p. 747-749.

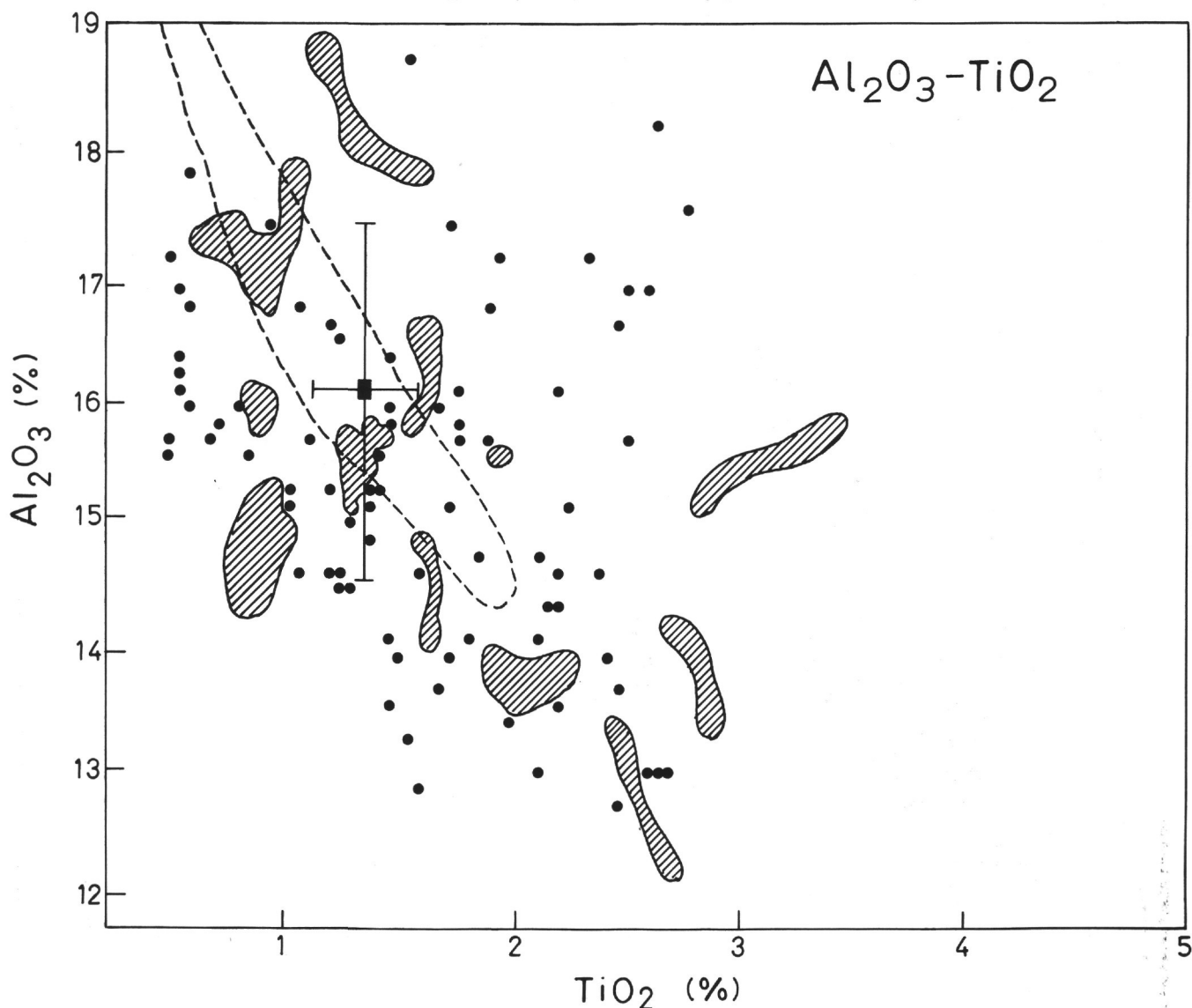


Figure 5. (Continued).

- Kay, R., Hubbard, N.J., and Gast, P.W., 1970. Chemical characteristics of oceanic ridge volcanic rocks: *J. Geophys. Res.*, v. 75, p. 1585.
- Kempe, D.R.C., 1974. The Petrology of the Basalts, Leg 26. *In* Davies, T.A., Luyendyk, B.P., et al., Initial Reports of the Deep Sea Drilling Project, Volume 26: Washington (U.S. Government Printing Office), p. 465-504.
- McLeod, N.S. and Pratt, R.M., 1973. Petrology of volcanic rocks recovered on Leg 18. *In* Kulm, L.D. von Heune, R., et al., Initial Reports of the Deep Sea Drilling Project, Volume 18: Washington (U.S. Government Printing Office), p. 935-945.
- Melson, W.G., Thompson, G., and Van Andel, T.J.H., 1968. Volcanism and metamorphism in the Mid-Atlantic Ridge. 22°N Latitude: *J. Geophys. Res.*, v. 73, p. 5925-5941.
- Miyashiro, A., Shido, F., and Ewing, M., 1969. Diversity and origin of abyssal tholeiite from the Mid-Atlantic Ridge near 24° and 30° north latitude: *Contrib. Mineral. Petrol.*, v. 23, p. 38.
- Ovenshine, A.T., Winkler, G.R., Andrews, P.B., and Gostin, V.A., 1975. Chemical analyses and minor element composition of Leg 29 Basalts. *In* Kennett, J.P., Houtz, R.E., et al., Initial Reports of the Deep Sea Drilling Project, Volume 29: Washington (U.S. Government Printing Office), p. 1097-1102.
- Robinson, P.T. and Whitford, D.S., 1974. Basalts from the Eastern Indian Ocean DSDP Leg 27. *In* Veevers, J.J., Heirtzler, J.R., et al., Initial Reports of the Deep Sea Drilling Project, Volume 27: Washington (U.S. Government Printing Office), p. 551-560.
- Sabine, P.A., 1972. Preliminary report on the basalt (Site 117). *In* Laughton, A.S., Berggren, W.A., et al., Initial Reports of the Deep Sea Drilling Project, Volume 12: Washington (U.S. Government Printing Office), p. 407-410.
- Scheidegger, K.F., 1972. Temperatures and compositions of magmas ascending beneath actively spreading mid-ocean ridges: Unpublished Ph.D. Dissertation, Oregon State University, Corvallis.
- Stewart, R.J., Natland, J.H., Glassley, W.R., 1973. Petrology of volcanic rocks from the North Pacific Ocean and the Bering Sea. *In* Creager, J.S., Scholl, D.W., et al., Initial Reports of the Deep Sea Drilling Project, Volume 19:

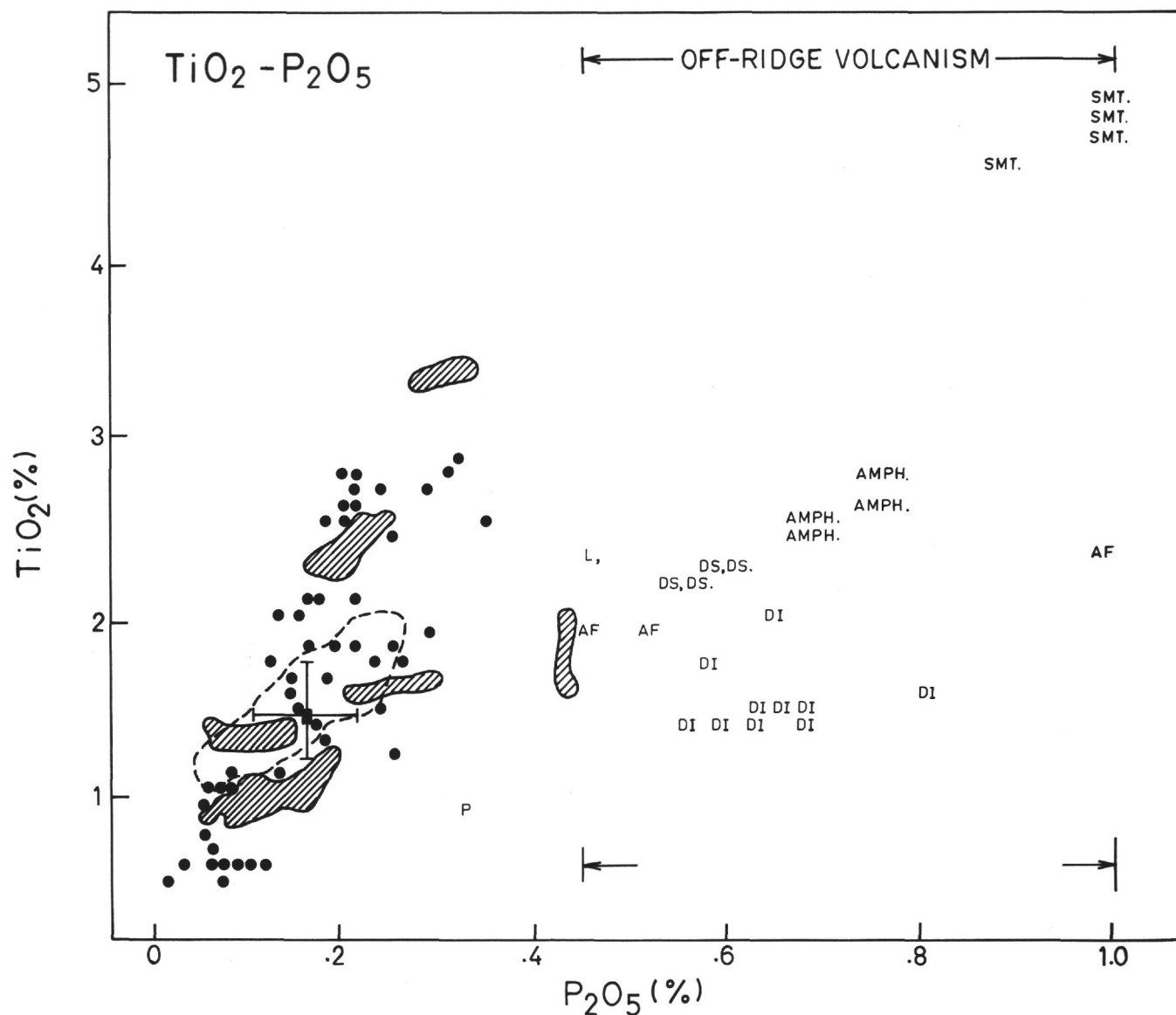


Figure 6. Plot of TiO_2 versus P_2O_5 . The cross represents the means and standard deviations of MORB. The dashed line outlines the MORB field. The shaded areas enclose TOPS basalt. The dots represent DSDP basement samples not classified as TOPS. DI = differentiated intrusive, DS = diabase sill, AL = alkalic flow, P = picrite, L = lamprophyre, SMT = alkali basalt from seamount. All samples above 44% P_2O_5 are obvious products of magmatic differentiation at off-ridge sites.

Washington (U.S. Government Printing Office), p. 615-628.

Thompson, G., Bryan, W.B., Frey, F.A., and Sung, C.M., 1973. Petrology and geochemistry of basalts and related rocks from Sites 214, 215, 216, DSDP Leg 22, Indian Ocean. In von der Borch, C.C., Sclater, J.G., et al., Initial Reports of the Deep Sea Drilling Project, Volume 22: Washington (U.S. Government Printing Office), p. 459-468.

Vallier, T.L., 1974. Synthesis of chemical analyses, igneous and metamorphic rocks recovered by the Deep Sea Drilling Project: Unpublished Report, Deep Sea Drilling Project.

Weibel, M. and Hsü, K.J., 1973. Chemistry of the Valencia trough volcanic rocks. In Ryan, W.B.F., Hsü, K.J., et al.,

Initial Reports of the Deep Sea Drilling Project, Volume 13: Washington (U.S. Government Printing Office), p. 770-771.

Wright, T.L., Benson, W.E., Melson, W.G., and Hart, S.R., 1972. Petrology of basaltic rocks collected from Leg 14. In Hayes, D.E., Pimm, A.C., et al., Initial Reports of the Deep Sea Drilling Project, Volume 14: Washington (U.S. Government Printing Office), p. 767-772.

Yeats, R.S., Forbes, W.C., Heath, G.R., and Scheidegger, K., 1973. Petrology and geochemistry of DSDP Leg 16 basalts, eastern equatorial Pacific. In van Andel, T.H., Heath, G.R., et al., Initial Reports of the Deep Sea Drilling Project, Volume 16: Washington (U.S. Government Printing Office), p. 617-640.

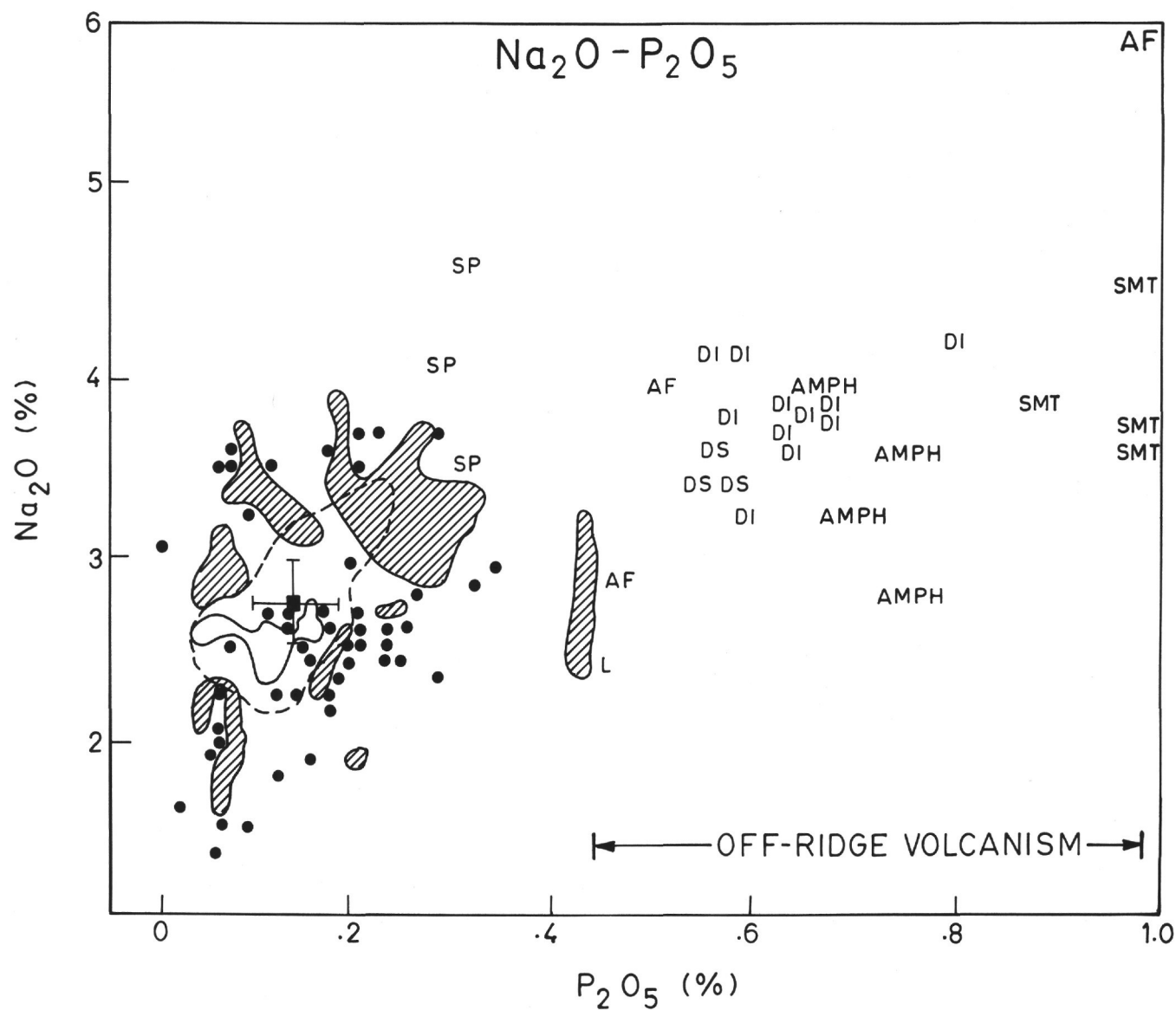


Figure 7. Covariant relations thought to be produced by partial melting of late magmatic phases. The crosses represent the means and standard deviations of MORB. The dashed line encloses the MORB field. The shaded areas enclose TOPS basalt. Circles represent DSDP basement samples not classified as TOPS basalt. DI = differentiated intrusive, DS = diabase sill, AL = alkalic flow, P = picrite, L = lamprophyre, SMT = alkali basalt from seamount, SP = spilites.

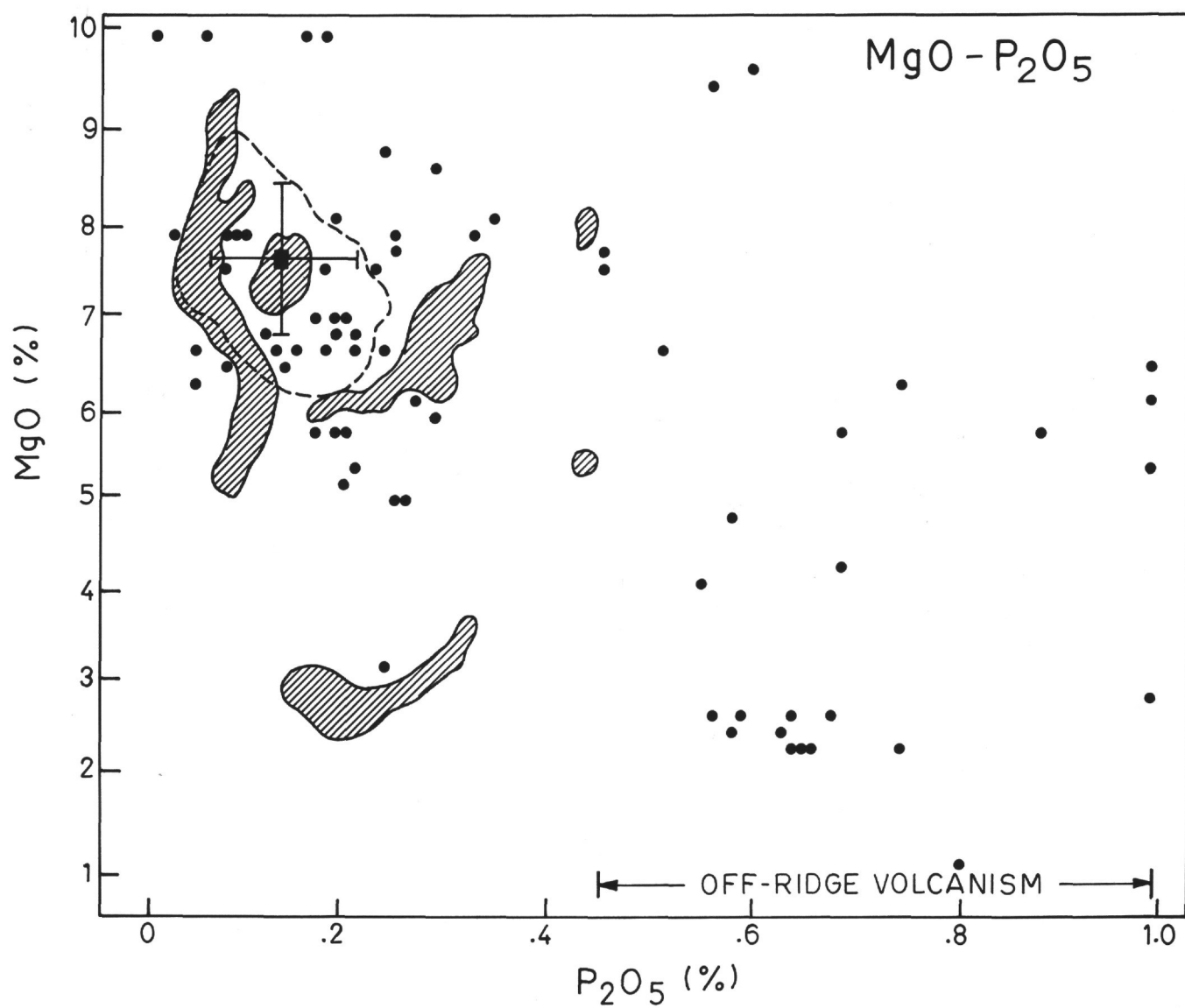


Figure 7. (Continued).

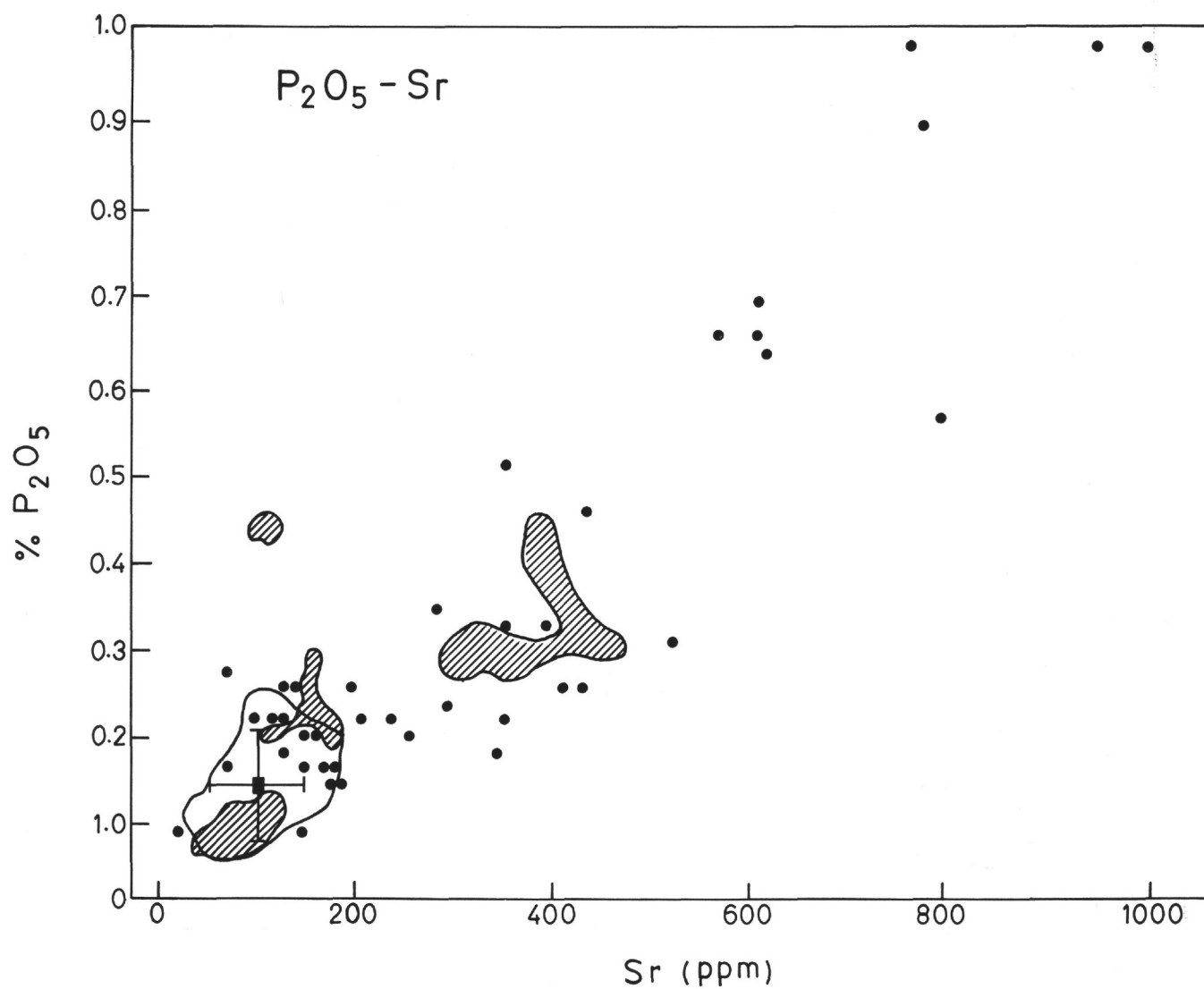


Figure 8. Covariant relations of LIL elements thought to be produced by partial melting of late magmatic phases. The crosses represents the means and standard deviations of MORB. The dashed line outlines the MORB field. Shaded areas enclose TOPS basalt. The dots represent all DSDP basement samples not classified as TOPS.

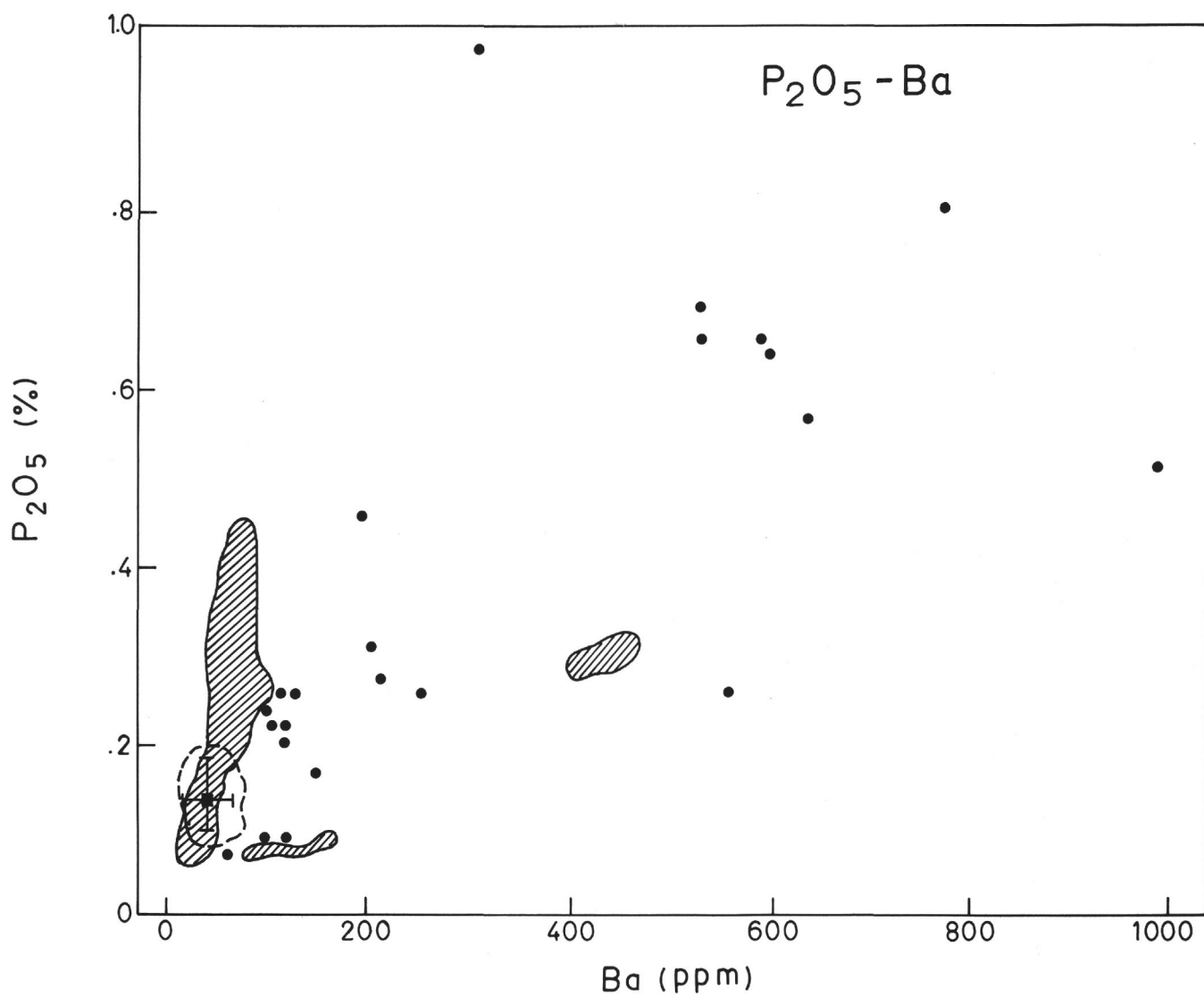


Figure 8. (Continued).

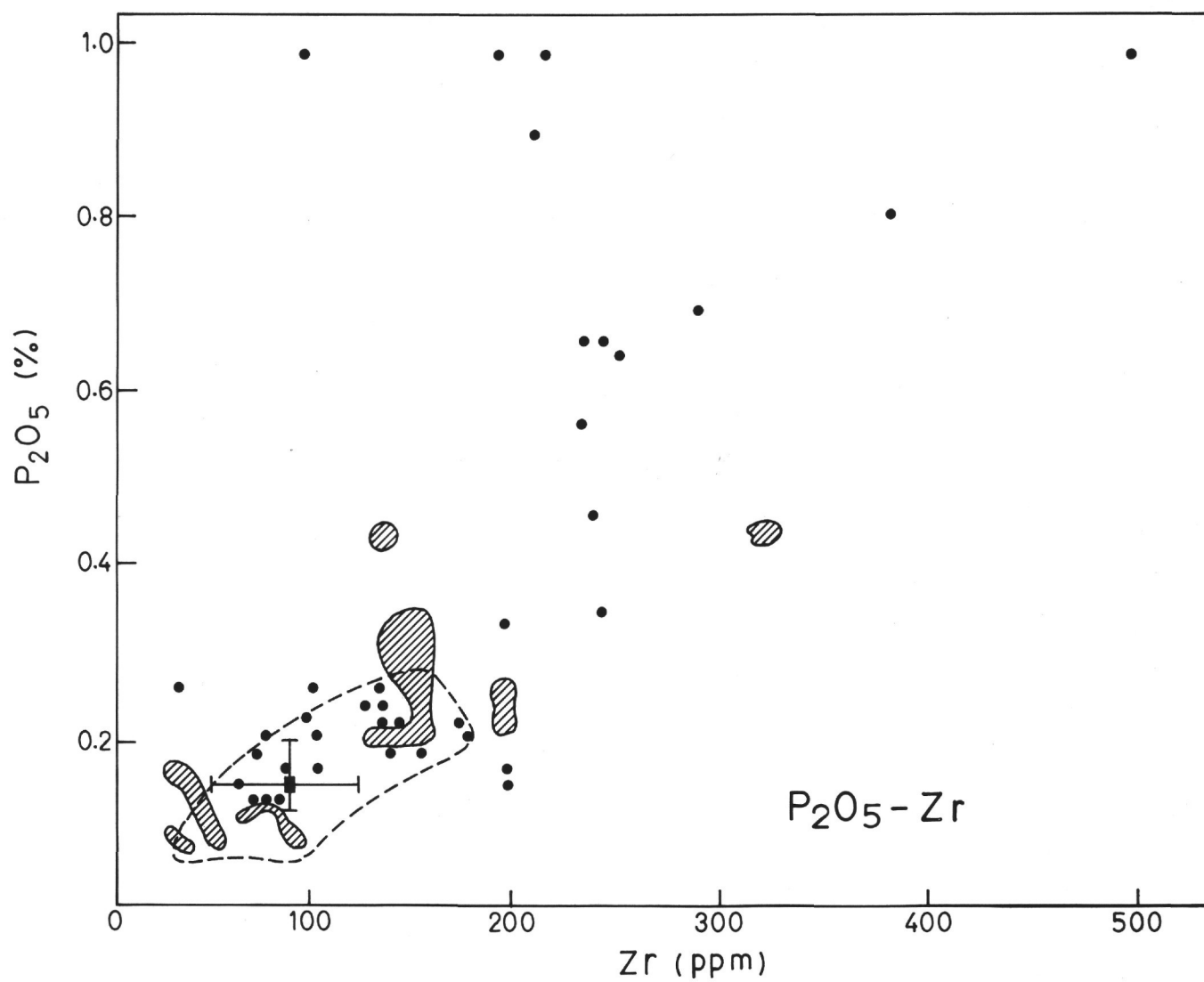
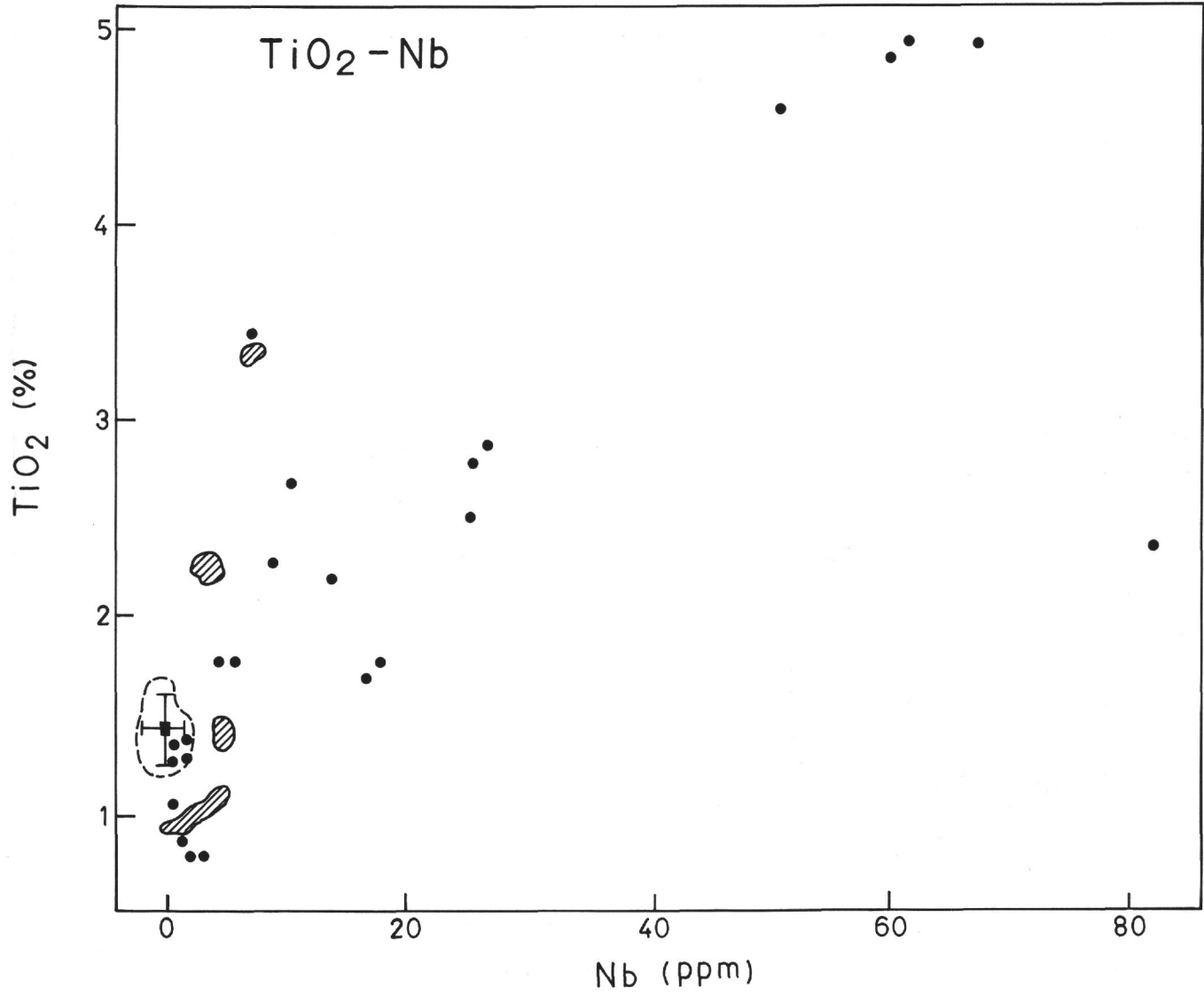


Figure 8. (Continued).



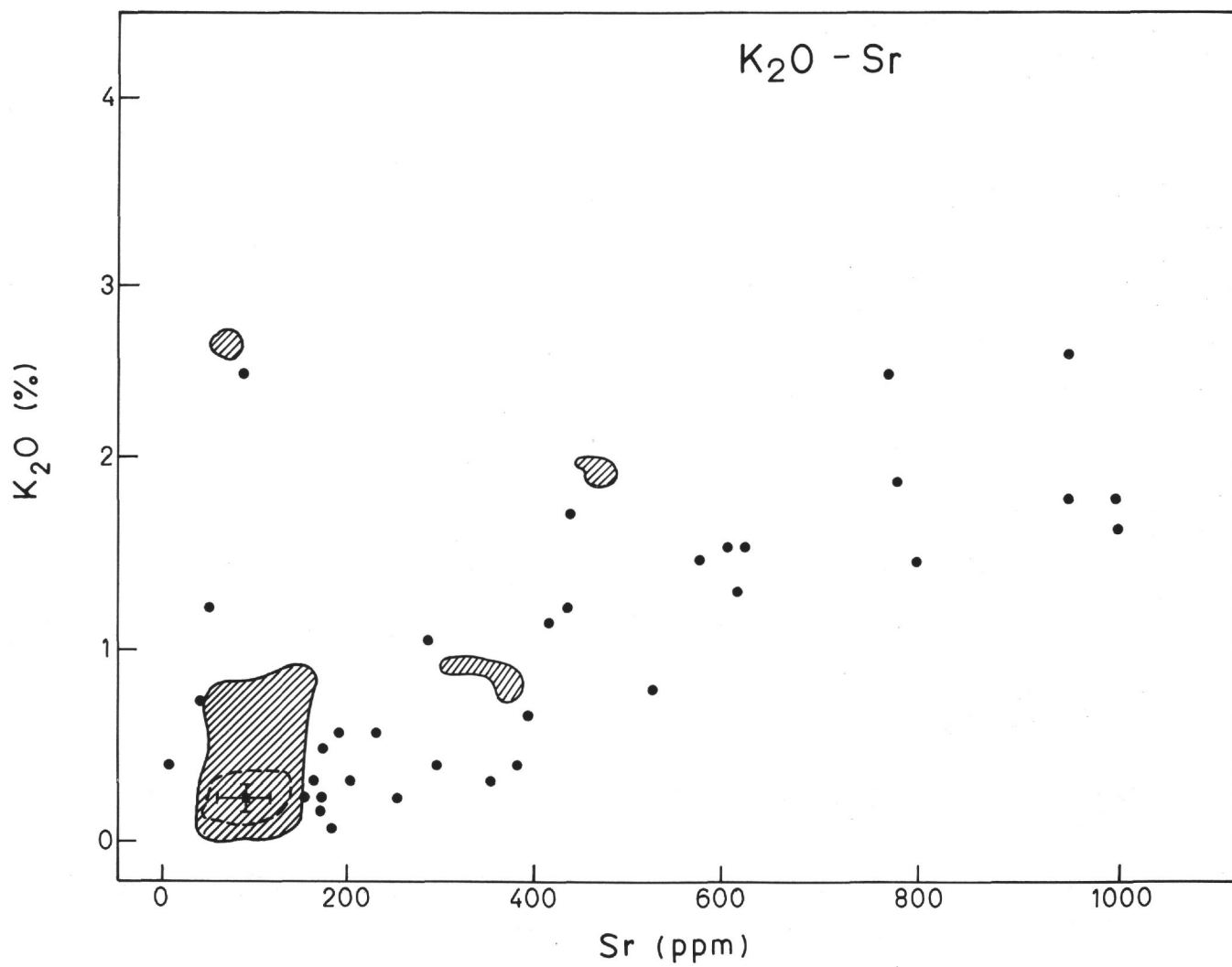


Figure 8. (Continued).

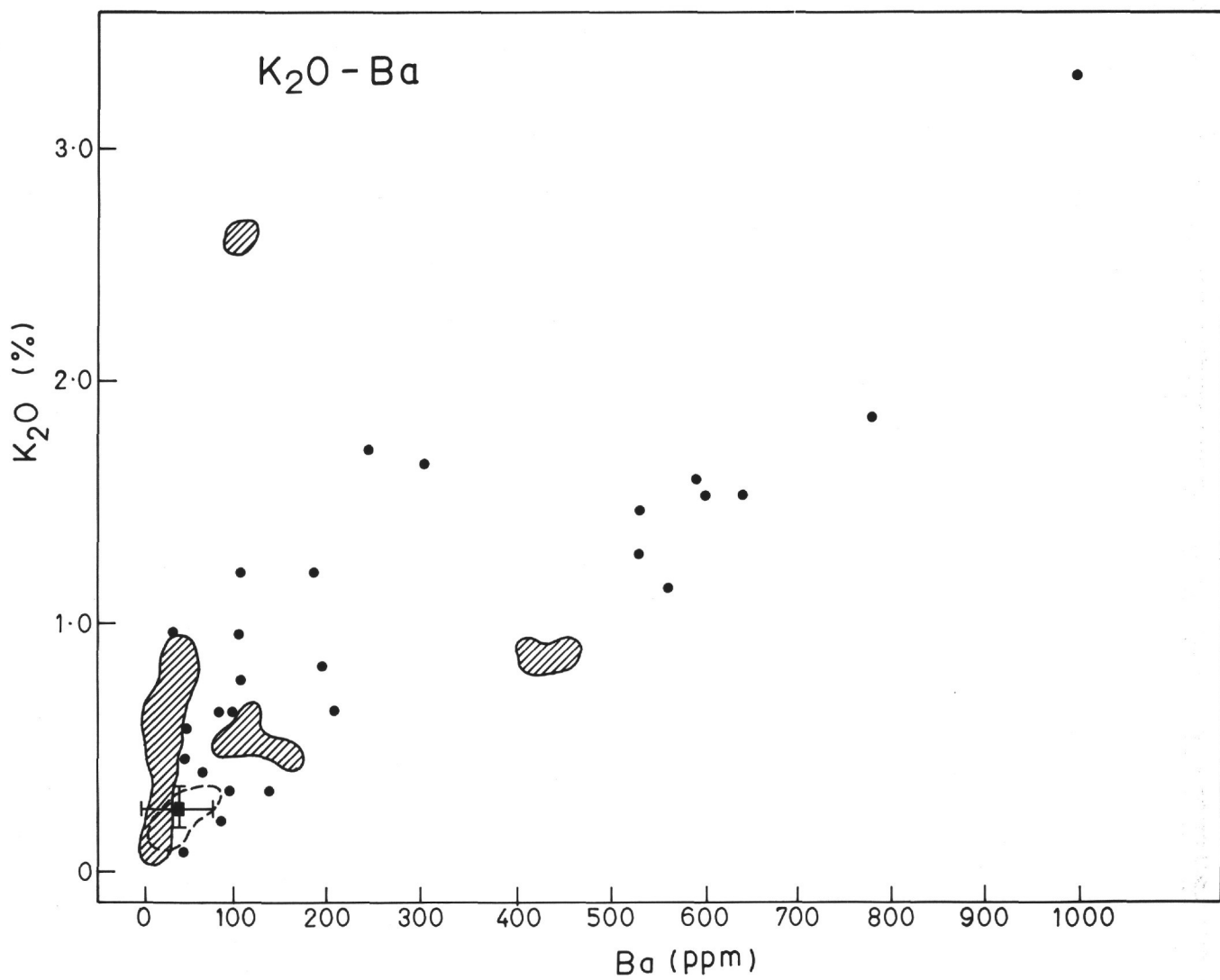


Figure 8. (Continued).

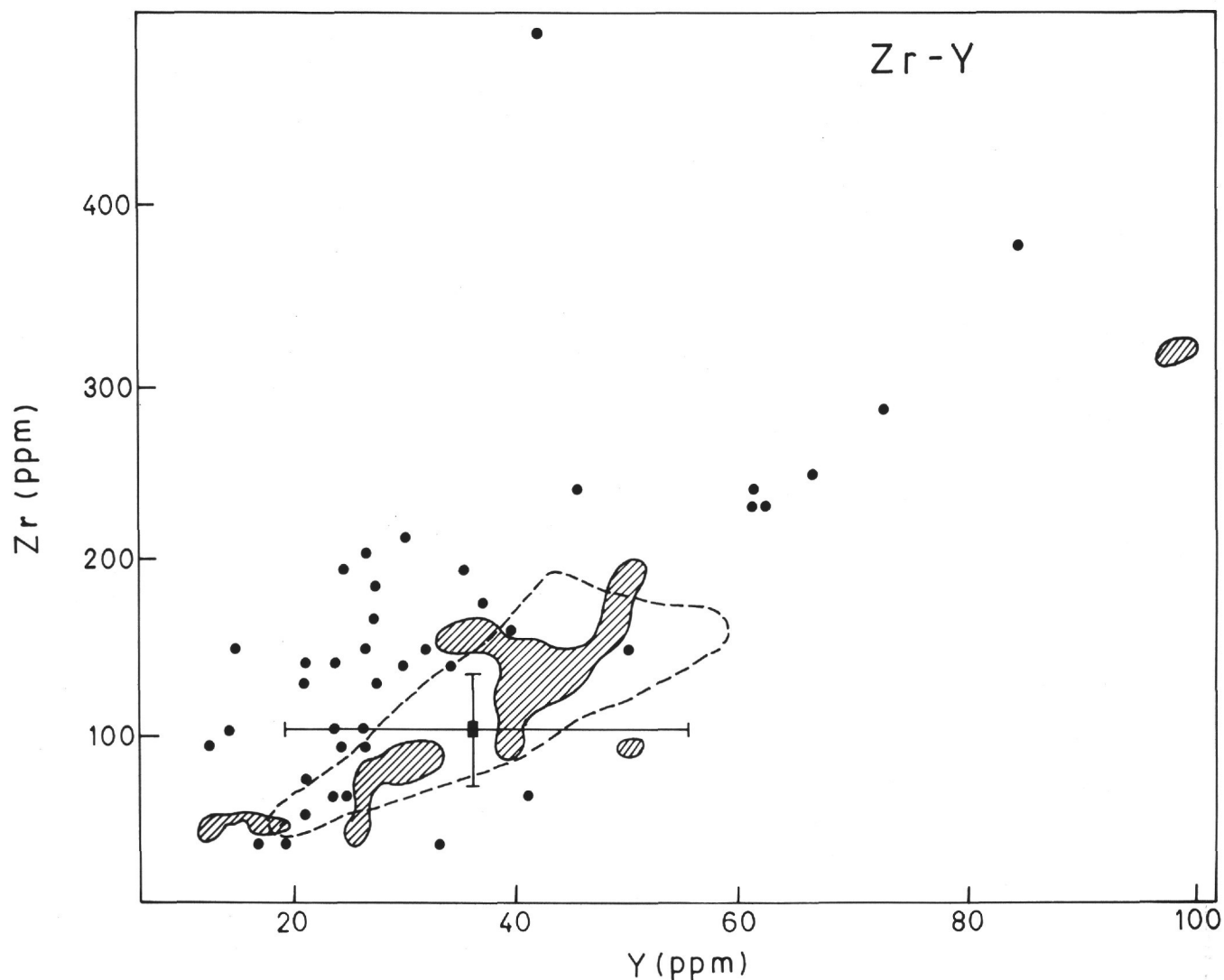


Figure 9. Covariant relations of LIL elements thought to be produced by partial melting of late magmatic phases. The crosses represent the means and standard deviations of MORB. The dashed line outlines the MORB field. Shaded areas enclose TOPS basalt. The dots represent all DSDP basement samples not classified as TOPS.

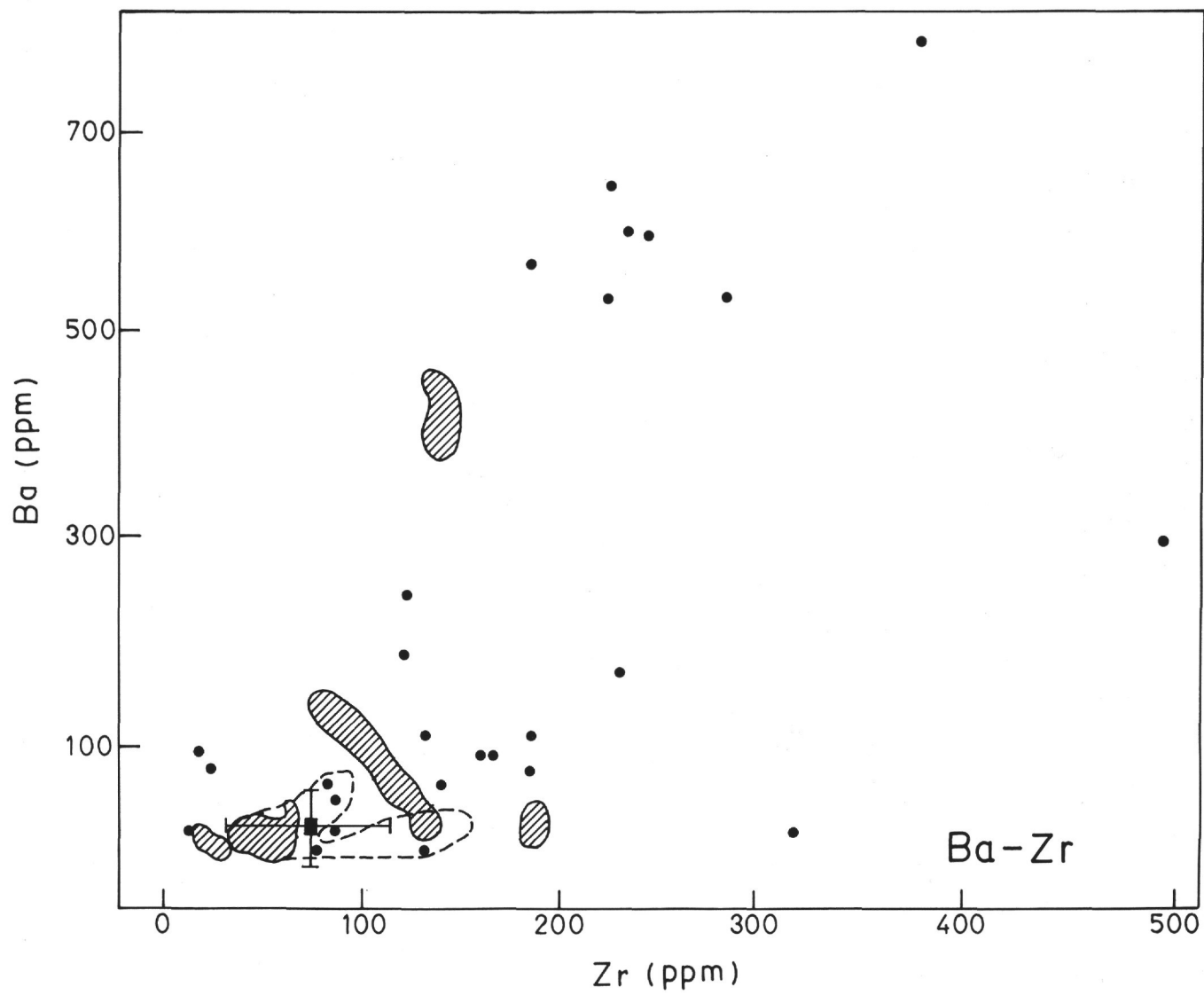


Figure 9. (Continued).

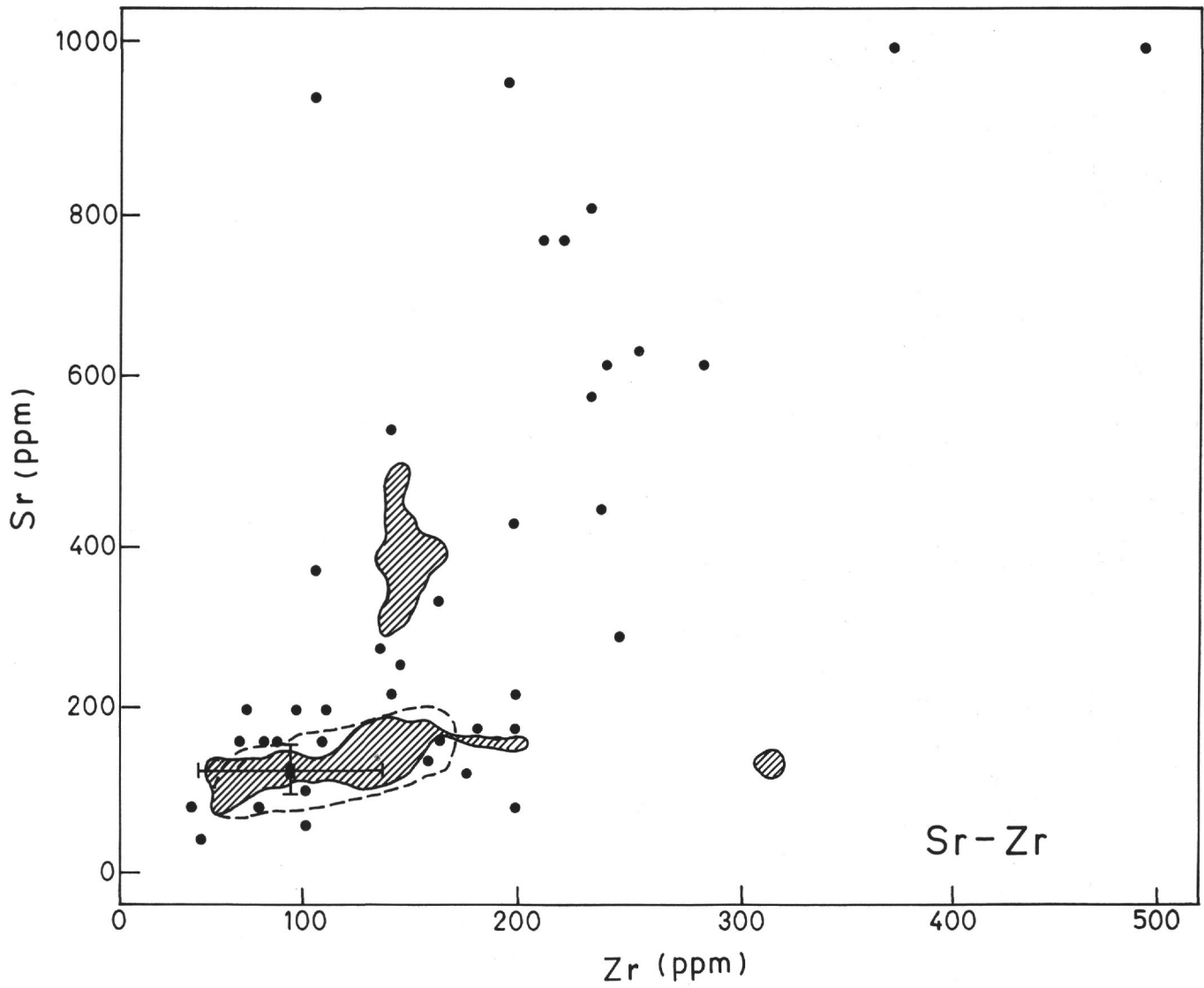


Figure 9. (Continued).

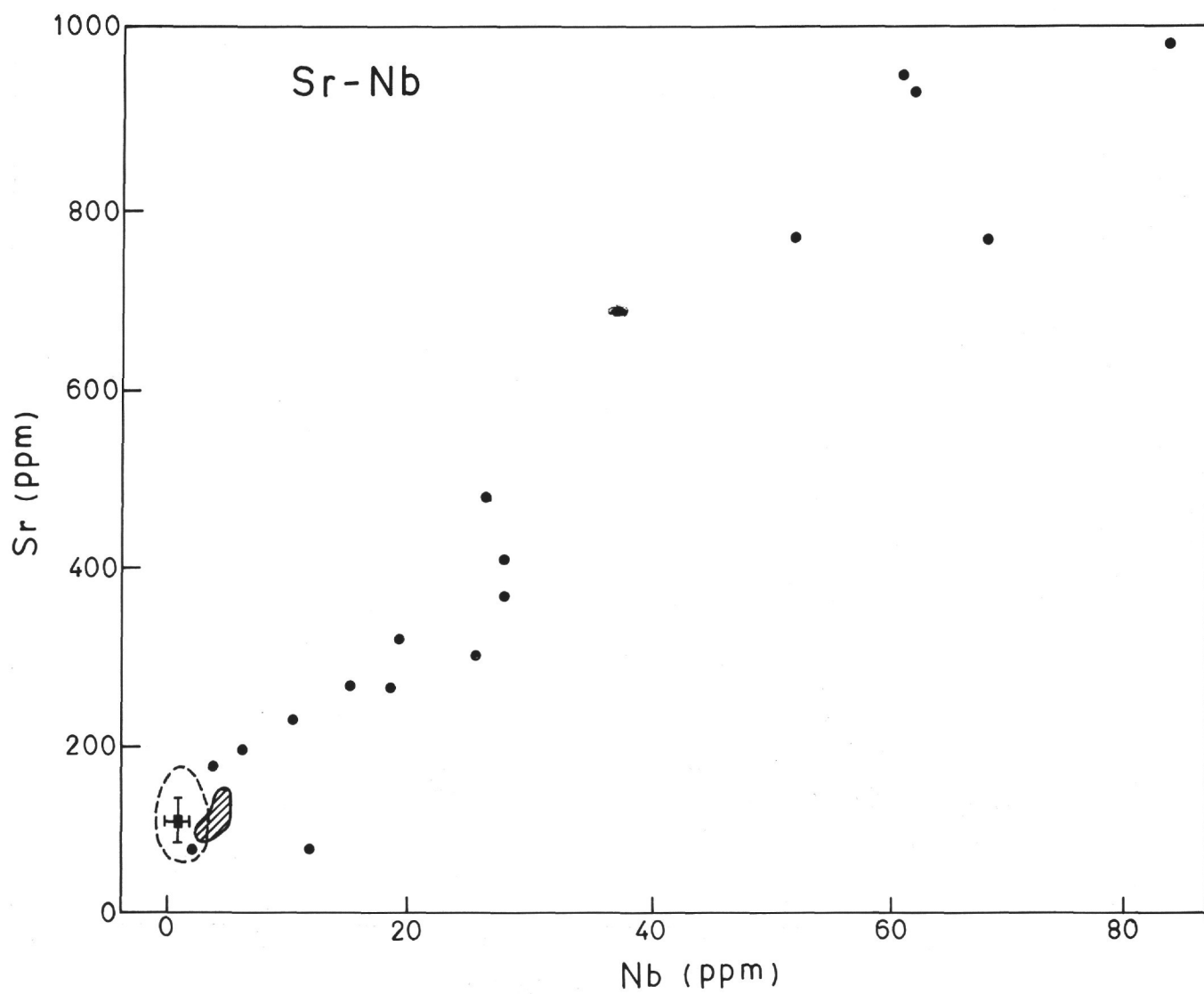


Figure 9. (Continued).

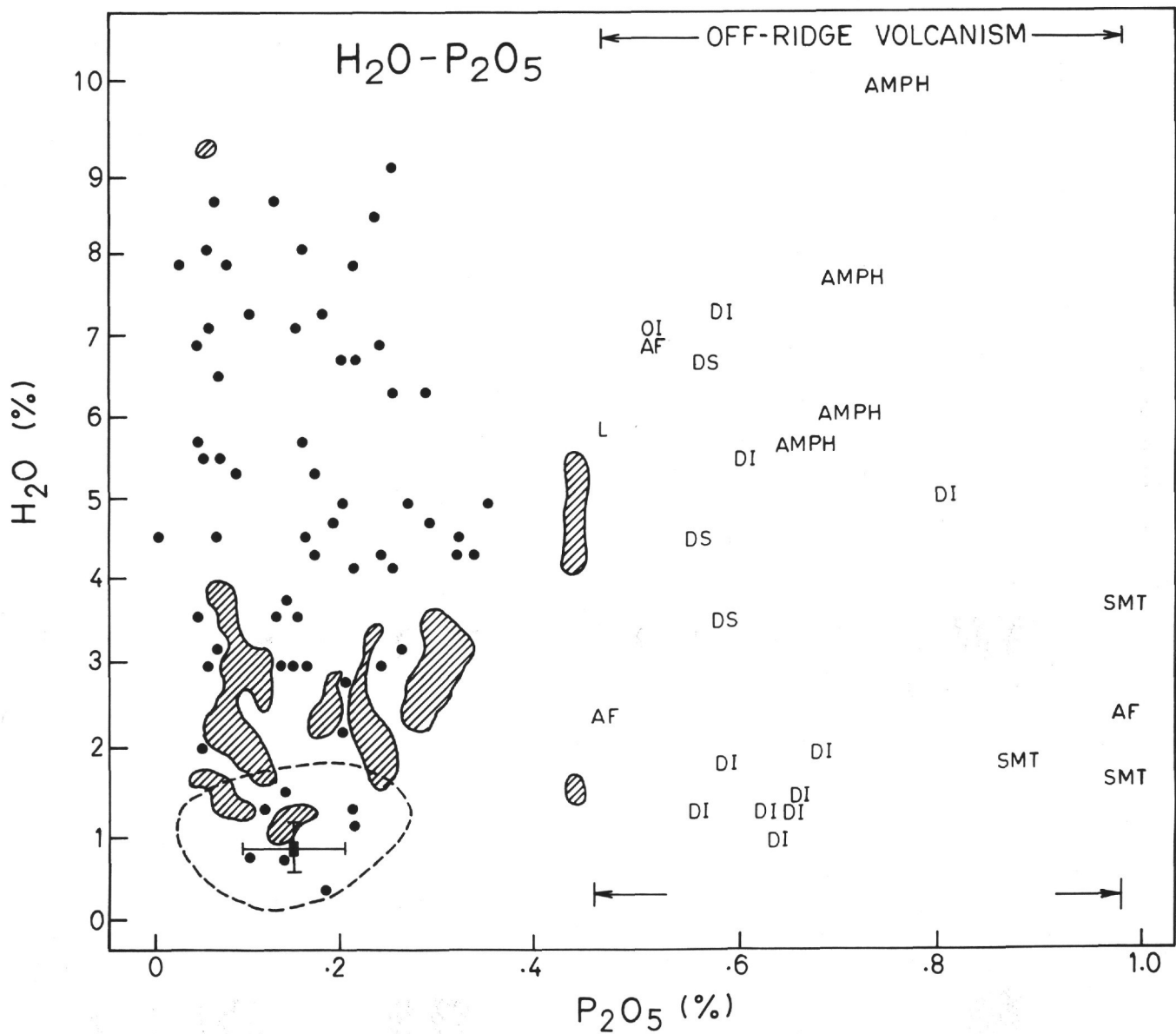


Figure 10. Plots of H_2O versus P_2O_5 and Al_2O_3 versus P_2O_5 demonstrating the lack of covariance in these groups of elements. The crosses represent the means and standard deviations of MORB. The dashed line encloses the MORB field. The shaded areas enclose TOPS basalt. The dots represent DSDP basement samples not classified as TOPS basalt. DI = differentiated intrusive, DS = diabase sill, AL = alkalic flow, P = picrite, L = lamprophyre, SMT = alkali basalt from seamount.

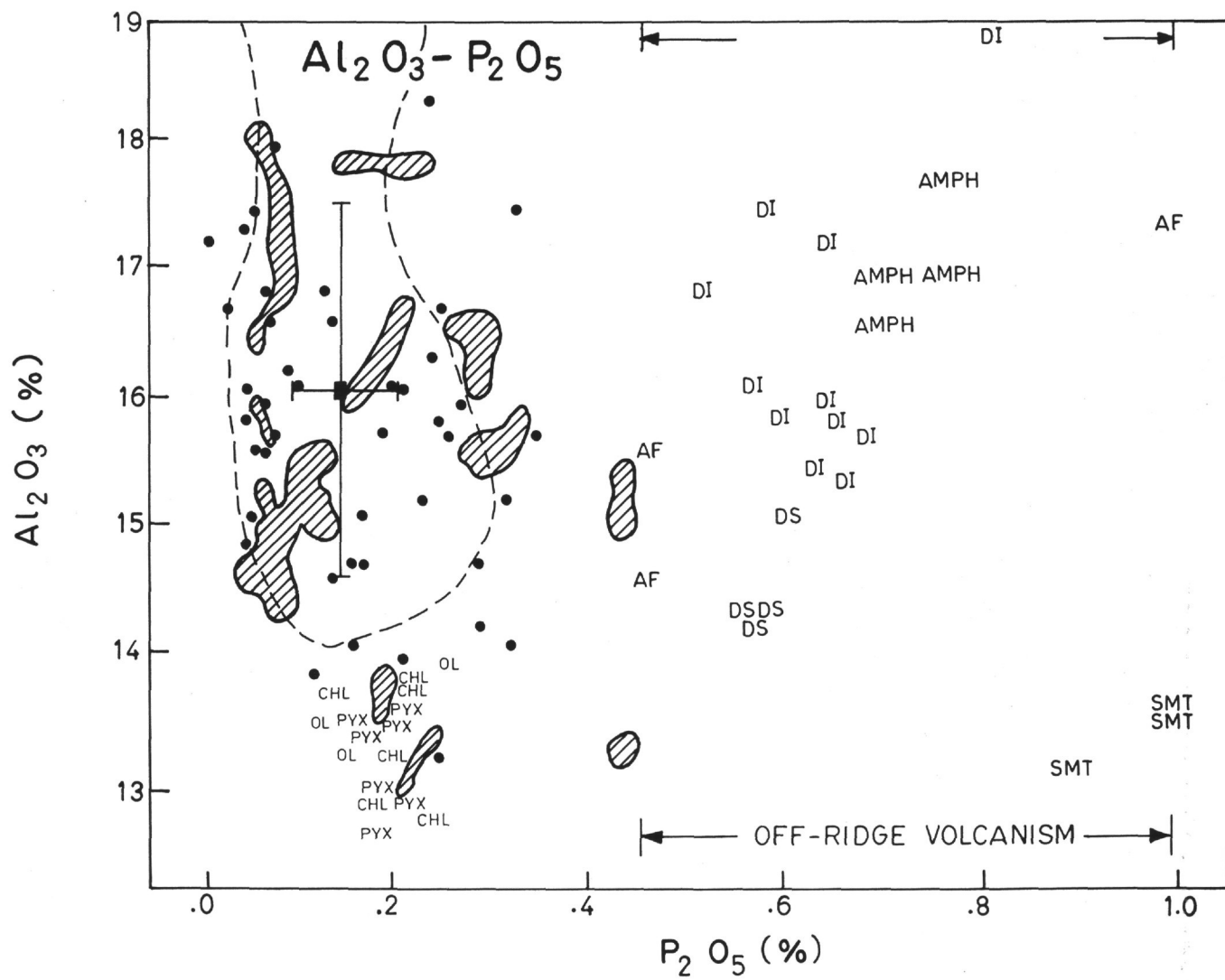


Figure 10. (Continued).

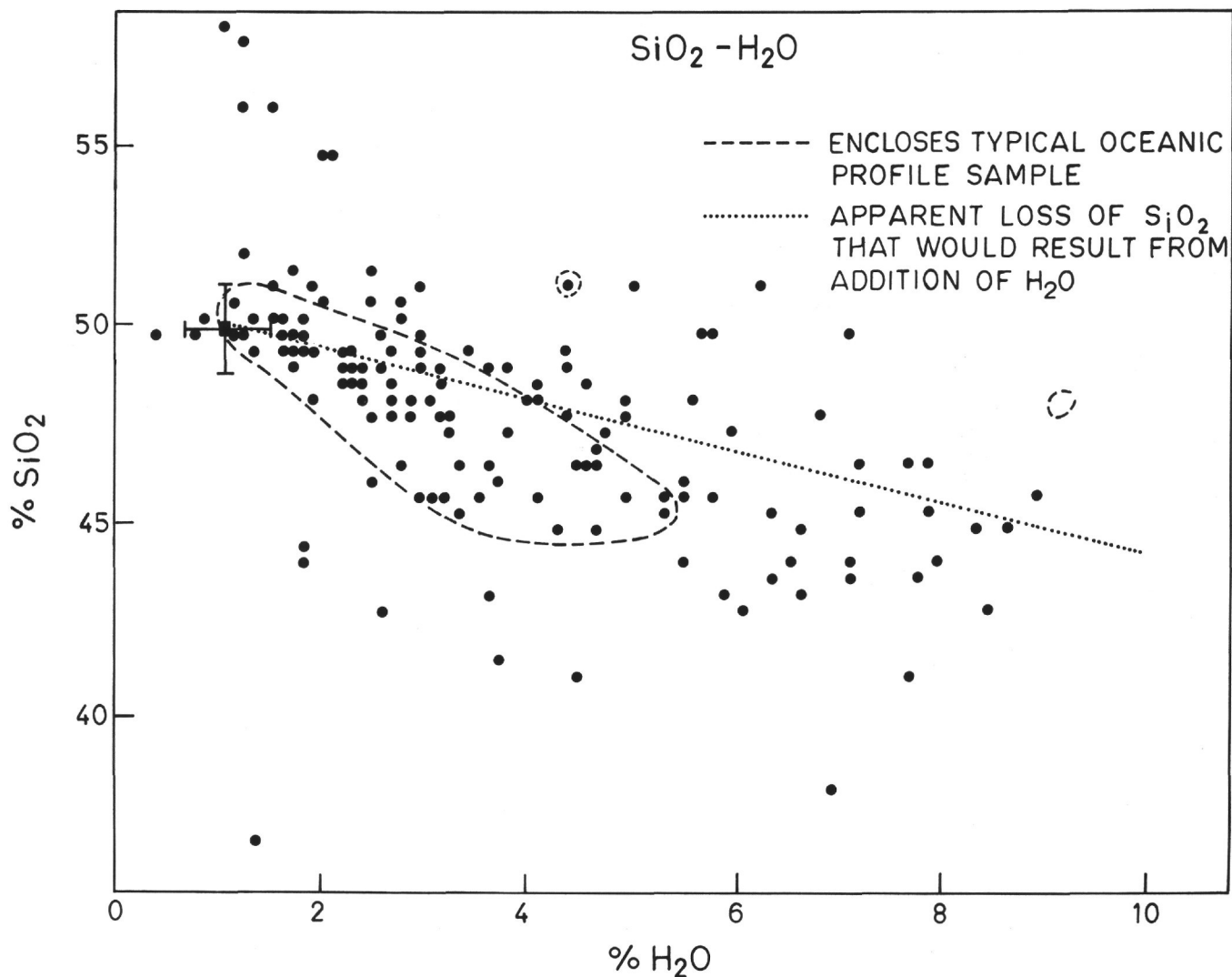


Figure 11. Covariant relations thought to be produced by seawater alteration of oceanic basalt. The crosses represent the mean and standard deviation of MORB. The dashed line encloses TOPS basalt. The dots represent all DSDP basement samples including TOPS basalt. The dotted lines represent the apparent losses in wt % SiO_2 and CaO that would result from the addition of 10% by weight of H_2O in a constant volume process.

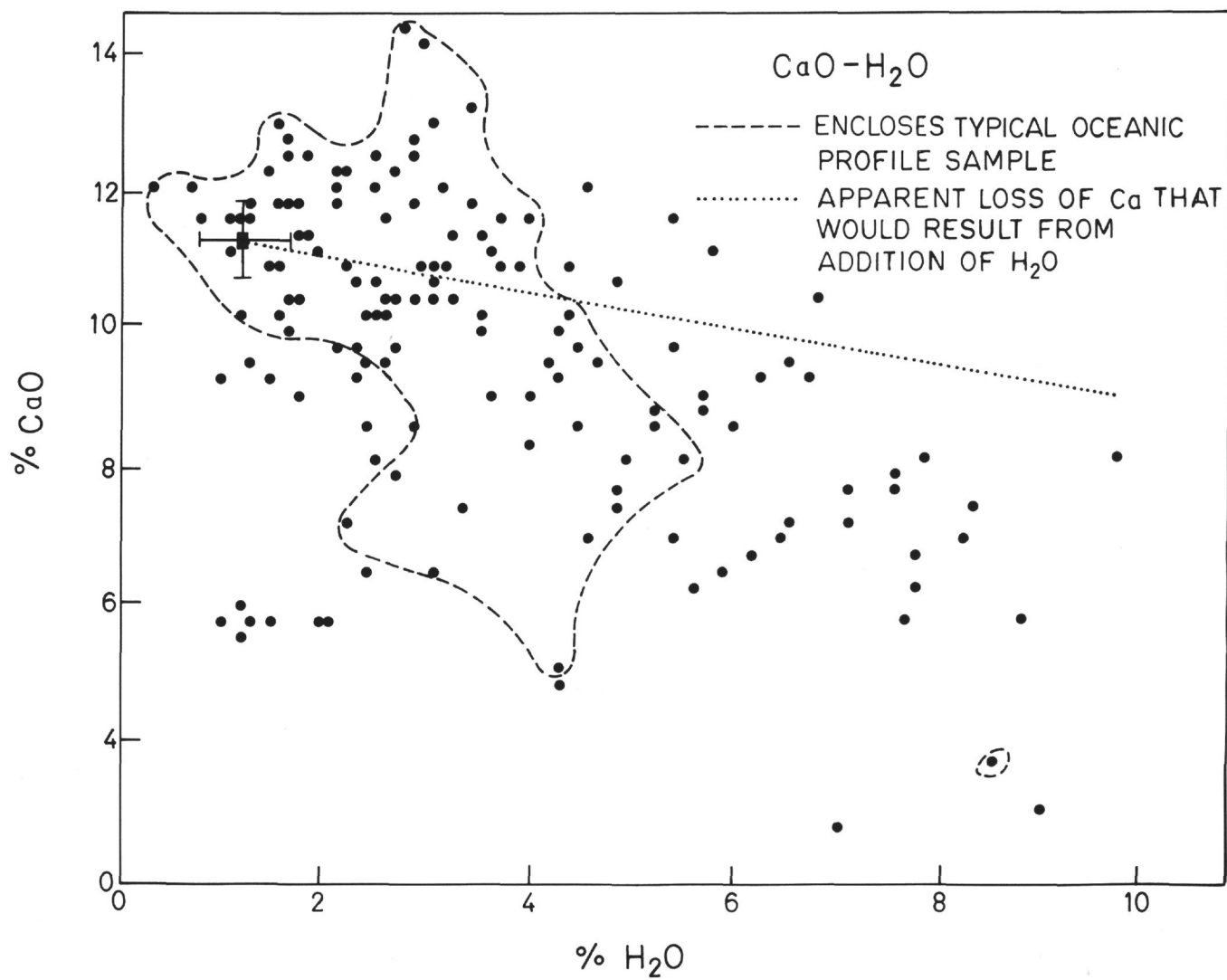


Figure 11. (Continued)

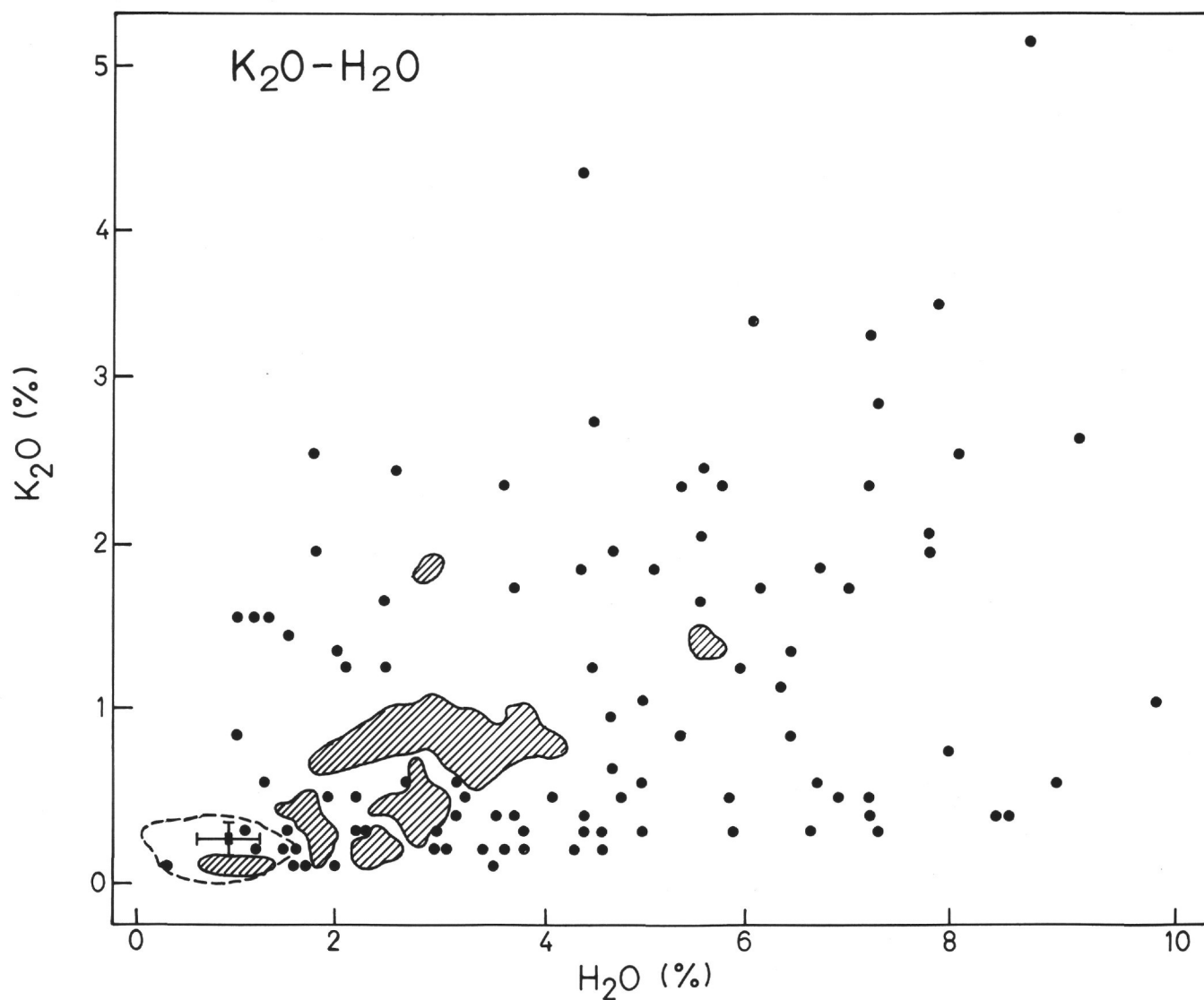


Figure 12. Covariant relations thought to be produced by seawater alteration of oceanic basalt. The crosses represent the means and standard deviation of MORB. The dashed line encloses MORB. The shaded areas enclose TOPS basalts. The dots represent all DSDP basement samples not classified as TOPS.

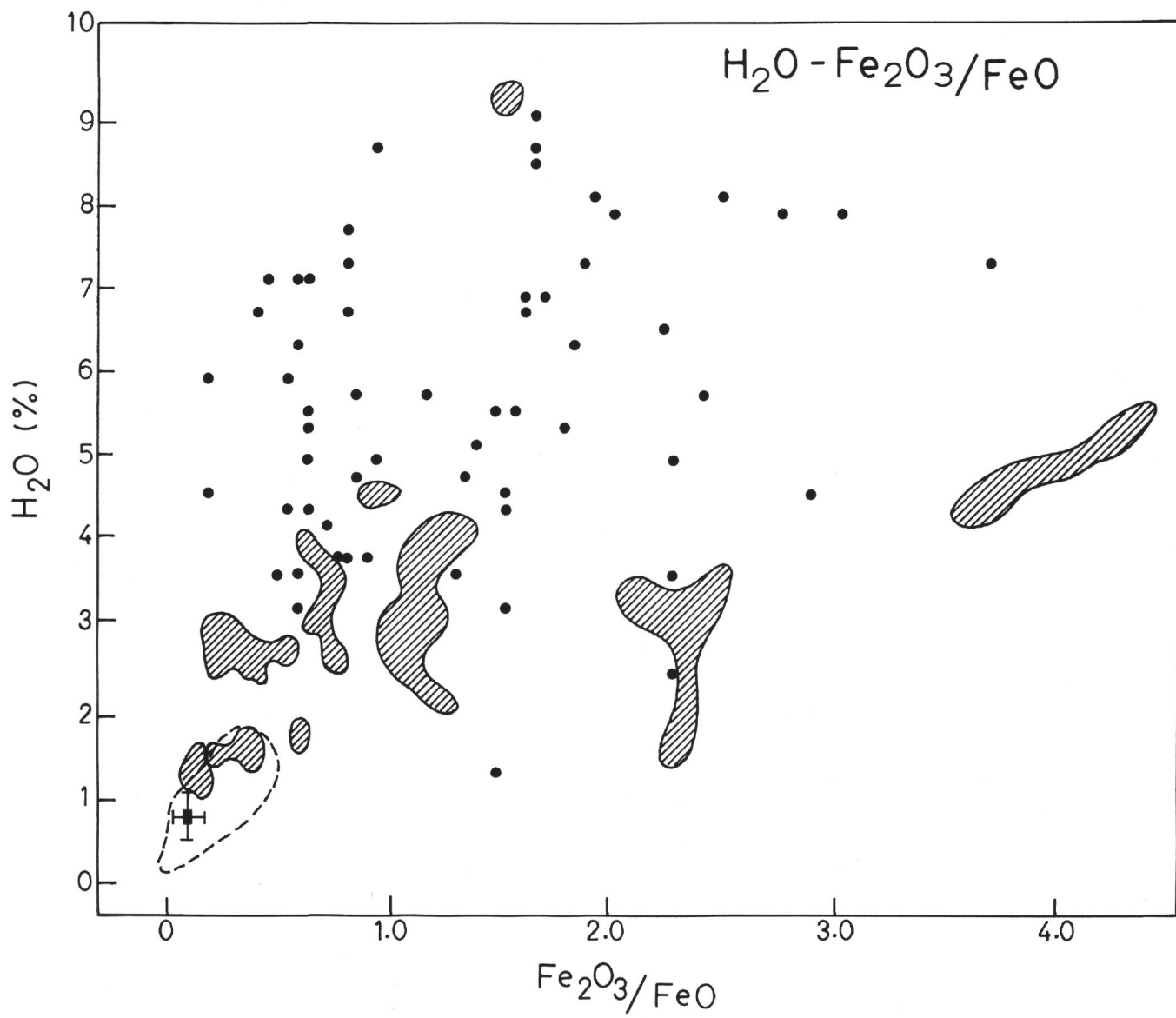


Figure 12. (Continued).

TABLE 5
Results of Multiple Regression Analysis of the Dependency of Element Concentration in Oceanic Basalt
(All DSDP Basement Samples Plus MORB) on Al₂O₃, P₂O₅, and H₂O as Independent Variables

Element	No. of Observations	Correlation Coefficient for all Variables	F Ratio ^a for All Variables	Constant	% Al ₂ O ₃		% P ₂ O ₅		% H ₂ O	
					Coefficient	T Test ^b	Coefficient	T Test ^b	Coefficient	T Test ^b
Total Fe as Fe ₂ O ₃	181	0.72	64.28	26.51	-1.02	-13.72	0.590	1.15	-0.04	-0.89
MnO	135	0.38	6.82	0.34	- .01	- 3.14	0.046	1.83	-0.005	-2.61
Co	56	0.58	8.88	105.00	-3.56	- 3.72	-20.38	-2.20	1.38	1.91
Ga	73	0.37	3.22	57.00	-1.95	- 2.70	0.197	0.03	-1.11	-1.92
Pb	18	0.50	1.59	-25.00	1.89	2.01	-2.55	-0.75	-0.82	-1.32
Mo	12	0.79	4.21	27.00	-1.84	- 3.48	1.71	0.59	0.63	1.64
Sc	25	0.58	3.41	101.00	-3.29	- 2.86	-4.94	-0.26	- .72	-0.91
Zn	44	0.50	4.56	173.00	-6.37	- 2.43	145.77	2.26	0.25	0.01

Note: Elements correlating primarily with Al₂O₃, major oxides in weight percent trace elements in ppm.

^aF ratio shows significance at the 95% confidence level above 2.68 for more than 120 observations and above 2.93 for more than 30 observations.

^bT test shows significance at the 95% confidence level above 1.98 for more than 120 observations and above 2.04 for more than 30 observations.

TABLE 6
Results of Multiple Regression Analysis of the Dependency of Element Concentrations in Oceanic Basalt
(All DSDP Basement Samples plus MORB) on Al₂O₃, P₂O₅, and H₂O as Independent Variable

Element	No. of Observations	Correlation Coefficient for All Variables	F Ratio ^a for All Variables	Constant	% P ₂ O ₅		% Al ₂ O ₃		% H ₂ O	
					Coefficient	T Test ^b	Coefficient	T Test ^b	Coefficient	T Test ^b
TiO ₂	181	0.77	88.88	4.49	2.39	13.02	-0.22	-8.21	-0.02	-0.92
MgO	181	0.62	35.25	11.85	-5.02	-9.87	-0.25	-3.43	-0.03	-0.63
Na ₂ O	181	0.66	46.84	1.91	2.13	11.85	0.03	1.31	-0.03	-2.13
Ba	96	0.72	40.58	-320.00	810.00	10.55	13.99	1.65	12.87	2.03
Sr	103	0.92	206.83	-166.00	957.00	24.83	8.68	1.61	10.43	2.67
Zr	107	0.73	39.13	109.00	251.00	10.61	-2.80	-0.83	1.62	0.65
Cr	76	0.53	12.64	-187.00	-367.00	-4.72	30.33	3.93	5.73	0.93
Cu	77	0.42	4.99	103.00	-110.00	-3.35	-1.32	-0.41	4.51	1.76
Ni	77	0.44	5.43	131.00	-170.00	-3.97	0.58	0.14	2.45	0.74
V	77	0.65	17.45	840.00	-354.00	-5.22	-31.28	-4.67	4.65	0.88
Y	91	0.45	6.86	40.50	23.22	3.28	-0.21	-0.21	-2.10	-2.65
Cl	26	0.67	5.59	21.30	559.00	3.56	-12.24	-0.31	39.86	1.83
Eu	13	0.95	89.93	1.53	4.86	12.34	-0.10	-0.72	-0.10	0.90
Hf	9	0.88	5.76	5.17	11.78	3.51	-0.34	-0.63	0.33	0.63
Nb	41	0.96	195.11	-17.48	75.22	23.23	0.37	0.48	1.67	3.81
Rb	47	0.63	8.56	-69.20	50.81	4.88	4.27	2.09	0.88	0.69
Th	14	0.94	32.50	-5.29	4.71	9.04	0.31	1.87	0.09	0.55
U	25	0.78	11.48	2.91	1.12	4.61	-0.01	-0.24	-0.03	-0.94

Note: Elements correlating primarily with P₂O₅, major oxides in weight percent trace elements in ppm.

^aF ratio shows significance at the 95% confidence level above 2.68 for more than 120 observations and above 2.93 for more than 30 observations.

^bT test shows significance at the 95% confidence level above 1.98 for more than 120 observations and above 2.04 for more than 30 observations.

TABLE 7
Results of Multiple Regression Analysis of the Dependency of Element Concentrations in Oceanic Basalt
(All DSDP Basement Samples Plus MORB) on Al₂O₃, P₂O₅, and H₂O as Independent Variables

Element	No. of Observations	Correlation Coefficient for All Variables	F Ratio for All Variables	Constant	% H ₂ O		% Al ₂ O ₃		% P ₂ O ₅	
					Coefficient	T Test ^b	Coefficient	T Test ^b	Coefficient	T Test ^b
SiO ₂	181	0.67	46.02	44.64	-0.85	-11.16	0.41	3.24	-0.09	-0.10
CaO	181	0.70	55.97	11.11	-0.49	-4.17	0.08	0.99	-4.17	-7.11
K ₂ O	181	0.69	52.90	-1.19	0.17	8.20	0.06	1.74	1.97	8.20
B	24	0.57	2.58	-4.37	9.08	2.22	-0.27	-0.05	-20.15	-0.49
Li	33	0.59	4.58	6.36	3.46	2.79	-0.41	-0.36	27.48	1.04

Note: Elements correlating primarily with H₂O, major element oxides in weight percent, trace elements in ppm.

^aF ratio shows significance at the 95% confidence level above 2.68 for more than 120 observations and above 2.93 for more than 30 observations.

^bT test shows significance at the 95% confidence level above 1.98 for more than 120 observations and above 2.04 for more than 30 observations.

TABLE 8
Classification of Elements in Oceanic Basalt According to Degree of Correlation
with Al-FeTi Group, LIL Group, and Seawater Alteration Group

	Al-FeTi Group	LIL Group	Alteration Group
Primary correlation	Al, Fe, Ti, Co, Sc, Pb, Ga, Mo, Mn	P, Ti, Na, Zr, Sr, Ba, Cl, Hf, Eu, Nb, Th, U, Rb, Mg, Cr, Ni, V	K, Si, Ca, Li, Cl, H ₂ O, B
Secondary correlation	Mg, Si, Zn, Ni, Rb, Th, Y, B, Yb, V, Cr	Si, Co, Zn, Ca, Y, Cu, Yb, K	Na, Mn, Ba, Rb, Pb, Sr, Mg, Yb, Eu, Zn, Th, U, Ga, Nb, Cr, Cu, Mo
No correlation	Eu, Sr, Ba, K, Na, Cu, Cl, Hf, Li, Nb, U, H ₂ O	Mn, Ga, Li, Rb, Mo, Sc, Al, Fe, B	Zr, Ti, Co, Ni, V, Hf, Sc, Al, Fe

TABLE 9
Results of Multiple Regression Analysis of the Dependence of Elemental Abundances in Oceanic Basalt
(All DSDP Basement Samples Plus MORB) on the Age of the Oceanic Crust
(as Determined Paleontologically in the Oldest Overlying Sediment)
and Depth of Drill Penetration Into Basement

Element	No. of Observations	Correlation Coefficient for All Variables	F Ratio ^a for All Variables	Age (10 ⁸ yr)		Depth (10 m)	
				Coefficient	T Test ^b	Coefficient	T Test ^b
CaO	193	0.38	13.21	-1.82	-5.01	0.43	2.98
K ₂ O	193	0.37	12.49	0.71	4.93	-0.15	-2.68
Na ₂ O	193	0.36	11.40	0.33	3.07	-0.20	-4.56
SiO ₂	193	0.25	6.00	-1.80	-3.44	0.35	1.70
Al ₂ O ₃	193	0.19	3.28	-0.52	-2.06	-0.06	-0.60
Y	88	0.28	3.15	-8.51	-2.08	0.21	1.82
Pb	18	0.50	2.60	-2.20	-1.86	0.03	4.11

Note: Major oxides in weight percent, trace elements in ppm.

^aF ratio shows significance at the 95% confidence level above 2.68 for more than 120 observations and above 2.93 for more than 30 observations.

^bT test shows significance at the 95% confidence level above 1.98 for more than 120 observations and above 2.04 for more than 30 observations.

TABLE 10

Results of Multiple Regression Analysis of the Dependence of Element Abundance in TOPS Basalt and MORB on the Age of the Oceanic Crust (as Determined Paleontologically in the Oldest Overlying Sediment) and Depth of Drill Penetration Into Basement

Element	No. of Observations	Correlation Coefficient for All Variables	F Ratio ^a for All Variables	Age (10 ⁸ yr)		Depth (10 m)	
				Coefficient	T Test ^b	Coefficient	T Test ^b
Na ₂ O	102	0.55	19.06	0.25	2.53	-0.20	-6.00
K ₂ O	102	0.53	18.15	0.54	6.02	-0.13	-4.02
SiO ₂	102	0.38	7.58	-1.42	-3.87	0.35	2.80
TiO ₂	102	0.37	7.48	0.35	2.62	-0.18	-3.86
MgO	102	0.36	7.04	-1.06	-3.36	0.38	3.42
MnO	85	0.36	6.40	0.04	3.35	-0.01	-1.15
CaO	102	0.31	5.38	-1.21	-3.11	0.37	2.77
P ₂ O ₅	87	0.31	4.23	0.04	1.69	-0.02	-2.90
Cu	42	0.58	9.67	-4.79	-3.25	0.27	0.08
Nb	16	0.73	6.96	3.93	3.69	-0.11	-2.45
Li	25	0.61	6.26	5.27	3.08	-2.81	-0.73
V	39	0.42	3.82	92.00	2.70	-12.26	1.48
Hf	6	0.84	3.50	0.46	1.23	-1.52	-2.32
Rb	20	0.52	3.09	3.46	2.23	-0.50	-0.26

Note: Major oxides in weight percent, trace elements in ppm.

^aF ratio shows significance at the 95% confidence level above 2.68 for more than 120 observations and above 2.93 for more than 30 observations.

^bT test shows significance at the 95% confidence level above 1.98 for more than 120 observations and above 2.04 for more than 30 observations.

APPENDIX A: LITERATURE SOURCES FOR CHEMICAL DATA ON OCEANIC BASALT USED IN THIS STUDY

1. DSDP Samples:

Sabine (1972); Wright et al. (1972); Honnorez and Fox (1973); Weibel and Hsü (1973); Donnelly et al. (1973); Bass et al. (1973); Yeats et al. (1973); MacLeod and Pratt (1973); Steward et al. (1973); Hekinian (1973); Thompson et al. (1973); Coleman (1974); Erlank et al. (1974); Kempe (1974); Ovenshine et al. (1975); Robinson and Whitford (1974).

Miyashiro et al (1969) Samples: A150-AM9, A150-AM1, A150-AM2, A150-AM5, A150-AM4, A150-AM15, A150-AM7, A150-AM16, V251-T9, V251-T87, V251-T3, V251-T11, V251-T1C, V251-T97, V251-T96, V251-T103, V251-T91, V251-T94, V251-T99, V251-T102, V2510T89.

Hekinian (1971) Samples: RC8-91, RC8-91A, RC8913, RC10-243.

Scheidegger (1972) Samples: W4-15, W8-2.

2. Ridge Basalts:

Melson et al. (1968) Samples: 2-1 and 2-2.

Aumento (1968) Samples: 1-1, 1-3, 56-2, and 56-3.

Engel et al. (1965) Samples: AD-2, AD-3, AD5-5, AD5-1, PVD-1, PVD-3, PVD-4C.

Hart et al. (1974) Samples: AD-1 (core), AD3-3 (glass), AD5-18 (margin).

Kay et al. (1970) Samples: AD150-7-4C, AD150-2-20, 13E, KD11, 4Z.

APPENDIX B

Correlation Matrices of Elemental Abundances in all DSDP Samples, TOPS Group, and Ridge Basalt

- = Strong negative correlation.
++ = Strong positive correlation, *R* greater than 0.5 with 99% confidence.

- = Weak negative correlation.

+ = Weak positive correlation, *R* greater than 0.3 with 95% confidence.

0 = No correlation.

ND = No data.

TABLE B1
All DSDP Data Correlation Matrix:
Major Elements, Physical Properties and Site Characteristics

		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1	Water depth		0	+	0	0	0	0	0	0	0	0	0	0	0	0	+	0	0	0	0
2	Sediment thickness	0		0	0	0	0	0	0	0	0	0	0	-	0	0	-	0	0	0	0
3	Age	+	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	Depth	0	0	0		+	+	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	Sonic velocity	0	0	0	+		0	0	0	-	0	0	++	-	-	--	0	0	0	++	--
6	Density	0	0	0	+	0		0	0	--	0	+	++	++	+	-	0	-	0	0	-
7	SiO ₂	0	0	0	0	0	0		0	0	0	0	0	0	0	--	0	0	0	0	0
8	Al ₂ O ₃	0	0	0	0	0	0	0		-	--	0	0	0	0	0	0	0	0	--	0
9	TiO ₂	0	0	0	0	-	--	0	-		+	0	0	+	0	0	+	++	0	0	0
10	Total iron as Fe ₂ O ₃	0	0	0	0	0	0	0	--	+		-	0	0	0	0	+	0	0	++	0
11	MgO	0	0	0	0	0	+	0	0	0	-		0	-	-	0	0	--	0	0	0
12	CaO	0	-	0	0	++	++	0	0	0	0	0		-	--	--	0	-	0	0	-
13	Na ₂ O	0	0	0	0	-	++	0	0	+	0	-	-		0	0	0	++	0	0	0
14	K ₂ O	0	0	0	-	+	0	0	0	0	-	--	0		+	0	0	+	0	-	+
15	H ₂ O	0	-	0	0	--	--	--	0	0	0	0	--	0	+		0	0	0	-	+
16	MnO	+	0	0	0	0	0	0	0	+	+	0	0	0	0	0		0	0	0	0
17	P ₂ O ₅	0	0	0	0	0	-	0	0	++	0	--	-	++	+	0	0		0	0	0
18	Fe ₂ O ₃	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0
19	FeO	0	0	0	0	++	0	0	--	0	++	0	0	0	-	-	0	0	0		++
20	Fe ₂ O ₃ /FeO	0	0	0	0	--	-	0	0	0	0	0	-	0	+	+	0	0	0	++	

Note: -- = strong negative correlation; ++ = strong positive correlation, R greater than 0.5 with 99% confidence; - = weak negative correlation; + = with positive correlation, greater than 0.3 with 95% confidence; 0 = no correlation; ND = no data.

TABLE B2
All DSDP Data Correlation Matrix Major Properties Versus Trace Elements

	Ba	Sr	Zr	Cr	Co	Cu	Ca	Ni	V	Y	B	Cl	Eu	Hf	Li	Pb	Mo	Nb	Rb	Sc	Th	U	Yb	Zn	S
Water depth	-	0	-	+	0	0	0	0	0	0	0	0	+	0	-	0	0	0	0	+	0	0	0	0	0
Sediment thickness	0	0	0	0	0	0	0	0	0	0	0	0	0	0	+	-	0	0	0	0	0	0	+	0	0
Age	0	0	-	0	0	0	0	0	0	-	0	-	0	0	-	-	0	0	0	0	-	0	0	0	0
Basement depth	0	0	0	0	0	0	0	0	0	0	0	0	-	0	-	0	-	0	0	-	-	0	-	0	0
Sonic velocity	0	-	0	0	--	-	+	0	+	++	ND	--	-	--	0	--	+	-	0	ND	0	-	ND	0	--
Density	-	-	-	+	-	0	+	0	++	+	ND	-	--	ND	-	-	+	--	-	ND	-	ND	ND	+	0
SiO ₂	0	0	0	0	-	-	0	-	-	0	-	0	0	0	--	0	0	--	0	0	-	+	-	0	0
Al ₂ O ₃	0	0	0	+	-	0	0	0	-	0	0	0	+	0	0	+	--	0	0	-	0	+	0	0	0
TiO ₂	0	++	+	--	0	0	0	0	++	0	0	++	+	++	0	+	0	++	+	+	+	+	+	+	+
Total iron as Fe ₂ O ₃	0	0	0	-	++	0	0	0	++	0	+	0	0	+	0	0	+	0	0	0	0	-	0	0	+
MgO	--	--	--	++	+	0	0	++	+	0	0	-	--	0	0	-	-	--	0	-	--	0	-	0	-
CaO	--	--	--	++	0	0	0	++	0	0	0	--	--	0	-	0	-	--	0	-	--	0	-	0	-
Na ₂ O	++	++	+	--	-	0	0	--	-	0	-	0	++	++	0	++	0	++	++	0	+	++	0	0	0
K ₂ O	++	++	++	0	+	+	0	0	0	0	++	0	0	+	+	0	0	0	0	0	+	-	++	0	0
H ₂ O	0	0	0	0	+	+	0	0	0	0	++	0	0	+	+	0	0	0	0	0	+	-	++	0	0
MnO	0	0	0	0	0	0	0	0	0	0	ND	0	0	+	0	0	0	0	0	0	0	0	++	0	0
P ₂ O ₅	+	++	++	-	-	-	0	-	--	0	0	++	++	++	+	+	0	++	++	0	++	++	0	+	0
Fe ₂ O ₃	0	0	0	0	0	0	0	+	0	0	+	+	ND	ND	++	ND	ND	0	0	0	+	0	0	0	0
FeO	0	0	0	--	0	0	0	0	+	0	0	-	ND	ND	-	ND	ND	0	-	0	-	--	0	0	+
Fe ₂ O ₃ /FeO	0	0	0	0	0	0	0	0	0	0	0	+	ND	ND	++	ND	ND	0	++	0	+	++	+	0	0

TABLE B3
All DSDP Data Correlation Matrix Trace Elements

	Ba	Sr	Zr	Cr	Co	Cu	Ga	Ni	V	Y	B	Cl	Eu	Hf	Li	Pb	Mo	Nb	Rb	Sc	Th	U	Yb	Zn	S
Ba		++	+	-	-	-	0	-	--	0	0	++	++	+	+	++	0	++	++	0	++	+	0	0	0
Sr	++		++	0	0	0	0	0	-	0	0	++	++	ND	0	ND	ND	++	+	0	++	++	0	0	0
Zr	+	++		0	-	0	++	0	0	++	0	0	+	++	0	+	0	++	+	0	++	++	0	0	0
Cr	-	0	0		0	0	0	++	0	0	0	ND	ND	ND	0	ND	ND	0	0	--	ND	ND	0	0	ND
Co	-	0	-	0		+	0	+	+	-	+	ND	ND	ND	ND	ND	ND	+	0	0	ND	-	0	+	ND
Cu	-	0	0	0	0		0	0	+	0	0	ND	ND	ND	0	ND	ND	+	0	0	ND	-	0	0	ND
Ga	0	0	++	0	0	0		0	0	+	0	ND	ND	ND	+	ND	ND	++	0	+	ND	+	++	0	ND
Ni	-	0	0	++	+	0	0		0	0	0	ND	ND	ND	+	ND	0	0	0	0	ND	-	0	0	ND
V	--	-	0	0	+	+	0	0		0	+	ND	ND	ND	-	ND	0	0	0	+	ND	-	+	0	ND
Y	0	0	++	0	-	0	+	0	0		-	0	ND	ND	0	ND	ND	0	0	0	+	+	+	0	0
B	0	0	0	0	+	0	0	0	+	-		ND	ND	ND	0	ND	ND	ND	ND	ND	ND	0	ND	ND	ND
Cl	++	++	0	ND	ND	ND	ND	ND	ND	0	ND		ND	ND	ND	ND	ND	+	+	ND	+	ND	ND	ND	0
Eu	++	++	+	ND	ND	ND	ND	ND	ND	ND	ND	ND		++	ND	+	+	ND	ND	ND	+	+	0	ND	0
Hf	+	ND	++	ND	ND	ND	ND	ND	ND	ND	ND	ND	+		ND	+	0	+	ND	ND	+	ND	ND	ND	+
Li	+	0	0	0	ND	0	+	+	-	0	ND	ND	ND	ND		ND	ND	ND	+	ND	ND	ND	ND	0	ND
Pb	++	ND	+	ND	ND	ND	ND	ND	ND	ND	ND	ND	+	+	ND		0	+	ND	ND	+	+	ND	ND	0
Mo	0	ND	0	ND	ND	ND	ND	0	0	ND	ND	ND	+	0	ND	0		0	ND	ND	0	+	ND	ND	0
Nb	++	++	++	0	+	+	++	0	0	0	ND	+	ND	+	ND	+	0		++	ND	++	+	0	+	0
Rb	++	+	+	0	0	0	0	0	0	0	ND	+	ND	ND	+	ND	ND	++		ND	+	ND	ND	0	0
Sc	0	0	0	--	0	0	+	0	+	0	ND	ND	ND	ND	ND	ND	ND	ND	ND		ND	ND	+	ND	ND
Th	++	++	++	ND	ND	ND	ND	ND	ND	+	ND	+	+	+	ND	+	0	++	+	ND		+	ND	ND	0
U	+	++	++	ND	-	-	+	-	-	+	ND	ND	+	+	ND	ND	+	+	ND	ND	+		ND	ND	0
Yb	0	0	0	0	0	0	++	0	+	+	ND	ND	0	ND	ND	ND	ND	0	ND	+	ND	ND	ND	ND	ND
Zn	0	0	0	0	+	0	0	0	0	0	ND	ND	ND	ND	0	ND	ND	+	0	ND	ND	ND	ND	ND	ND
S	0	0	0	ND	ND	ND	ND	ND	ND	0	ND	0	0	+	ND	0	0	0	0	ND	0	0	ND	ND	ND

TABLE B4
Typical Ocean Profile Samples
Correlation Matrix Major Elements, Physical Properties, Site Characteristics

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1	Water depth		0	++	0	-	-	0	0	0	0	0	0	+	+	+	0	0	-	0
2	Sediment thickness	0		0	+	+	0	0	0	0	0	0	0	0	+	0	0	+	-	+
3	Age	++	0		+	0	0	0	0	0	0	0	0	0	0	0	+	0	0	0
4	Basement depth	0	+	+		+	++	+	0	-	0	+	0	-	-	0	0	-	--	0
5	Sonic velocity	-	+	0	+		++	0	0	--	0	0	++	-	--	--	0	--	--	++
6	Density	-	0	0	++	++		+	+	--	0	+	++	--	--	--	0	--	--	0
7	SiO ₂	0	0	0	+	0	+		0	0	0	0	0	0	0	--	0	0	--	+
8	Al ₂ O ₃	0	0	0	0	0	+	0		-	--	0	0	0	0	0	0	0	--	0
9	TiO ₂	0	0	0	-	--	--	0	-		++	-	--	++	+	0	0	++	0	0
10	Total iron as Fe ₂ O ₃	0	0	0	0	0	0	0	--	++		0	0	0	0	-	0	+	0	++
11	MgO	0	0	0	+	0	+	0	0	-	0		0	-	-	0	0	-	--	0
12	CaO	0	0	0	0	++	++	0	0	--	0	0		-	--	--	0	--	0	--
13	Na ₂ O	0	0	0	-	--	--	0	0	++	0	-	-		+	0	00	++	+	0
14	K ₂ O	+	0	0	-	--	--	0	0	+	0	-	--	+		++	0	+	+	++
15	H ₂ O	+	+	0	0	--	--	--	0	0	-	0	--	0	++		0	0	++	--
16	MnO	+	0	+	0	0	0	0	0	0	0	0	0	0	0	0		0	+	--
17	P ₂ O ₅	0	0	0	-	--	--	0	0	++	+	-	--	++	+	0	0		+	0
18	Fe ₂ O ₃	0	+	0	--	--	--	--	0	0	0	--	0	+	+	++	+	+	--	++
19	FeO	-	0	0	++	0	+	--	0	++	0	0	0	-	--	--	0	--	--	--
20	Fe ₂ O ₃ /FeO	0	+	0	-	--	-	-	0	0	0	--	--	0	++	++	+	+	++	--

TABLE B5
Typical Ocean Profile Samples Correlation Matrix Major Properties Versus Trace Elements

	Ba	Sr	Zr	Cr	Co	Cu	Ga	Ni	V	Y	B	Cl	Eu	Hf	Li	Pb	Mo	Nb	Rb	Sc	Th	U	Yb	Zn	S
Water depth	0	0	0	-	-	-	+	--	+	0	ND	0	++	++	-	++	++	++	+	++	++	+	ND	ND	ND
Sediment thickness	--	0	-	0	++	0	-	++	0	0	ND	-	+	+	0	-	++	-	-	-	+	+	0	0	+
Age	-	-	0	0	0	-	+	0	+	0	ND	-	+	+	0	0	++	0	0	0	++	+	0	0	++
Basement depth	0	-	-	0	-	0	0	0	0	0	ND	-	-	--	0	0	0	-	0	ND	-	-	-	0	0
Sonic velocity	0	--	0	0	ND	--	0	0	0	++	ND	-	-	-	--	-	-	-	-	ND	-	-	ND	0	--
Density	-	--	--	+	ND	--	0	0	0	++	ND	-	-	-	-	-	-	--	-	ND	ND	ND	ND	+	0
SiO ₂	0	0	0	0	-	-	0	--	0	+	0	+	0	-	0	++	0	-	++	+	0	0	-	--	0
Al ₂ O ₃	0	0	+	++	-	+	--	0	--	-	ND	0	0	-	0	++	-	-	+	--	0	0	0	--	0
TiO ₂	0	++	++	-	+	0	+	0	++	0	-	++	++	++	-	+	++	++	+	++	+	++	++	+	++
Total iron as Fe ₂ O ₃	0	0	++	--	+	0	+	0	++	+	-	++	++	--	+	++	0	0	++	+	+	0	0	+	+
MgO	0	0	-	0	+	0	0	+	+	0	ND	-	0	0	++	0	0	--	-	-	0	0	-	0	+
CaO	0	--	--	++	--	0	0	0	-	0	0	-	-	-	0	-	--	--	-	-	-	-	-	0	-
Na ₂ O	+	++	0	-	+	0	0	0	0	0	-	+	+	+	0	0	+	++	0	+	+	++	+	0	0
K ₂ O	+	+	0	0	0	++	-	0	0	-	+	++	++	+	0	0	0	++	++	+	++	++	++	+	0
H ₂ O	0	0	0	0	++	++	0	++	-	--	+	++	+	+	++	0	0	++	0	--	+	++	+	+	0
MnO	0	-	0	0	--	-	+	-	+	+	ND	-	+	+	0	0	+	0	+	+	+	++	0	++	+
P ₂ O ₅	+	++	++	0	+	0	0	0	0	+	-	+	+	++	0	+	+	++	+	+	+	++	++	+	+
Fe ₂ O ₃	0	+	0	0	+	++	0	+	0	-	+	++	ND	ND	0	ND	+	++	+	+	+	++	+	+	0
FeO	0	0	+	--	0	--	++	-	++	++	-	--	ND	ND	0	ND	ND	--	--	+	ND	-	0	0	0
Fe ₂ O ₃ /FeO	0	0	0	0	0	++	-	0	0	0	+	++	ND	ND	0	ND	ND	++	++	+	ND	-	+	+	0

TABLE B6
Typical Ocean Profile Samples: Correlation Matrix Trace Elements

	Ba	Sr	Zr	Cr	Co	Cu	Ga	Ni	V	Y	B	Cl	Eu	Hf	Li	Pb	Mo	Nb	Rb	Si	Th	U	Yb	Zn	S
Ba		++	0	0	0	0	0	0	0	0	ND	ND	++	++	0	0	++	++	++	+	+	0	+	0	0
Sr	++		+	0	++	0	0	0	0	-	+	ND	ND	0	ND	ND	ND	++	+	0	ND	+	+	+	+
Zr	0	+		-	0	-	+	-	++	++	-	+	ND	++	-	+	0	++	0	+	+	++	+	0	+
Cr	0	0	-		0	0	-	+	--	-	-	ND	ND	ND	0	ND	ND	ND	-	-	ND	0	-	0	ND
Co	0	++	0	0		-	+	++	0	0	0	ND	ND	ND	ND	ND	ND	ND	ND	0	ND	ND	ND	ND	ND
Cu	0	0	-	0	-		--	0	-	-	+	ND	ND	ND	ND	+	ND	ND	ND	ND	0	ND	ND	+	0
Ga	0	0	+	-	+	--		0	++	0	0	ND	ND	ND	-	ND	ND	ND	-	+	ND	ND	ND	0	ND
Ni	0	0	-	+	++	0	0		0	0	-	ND	ND	ND	++	ND	ND	ND	-	-	ND	ND	ND	0	ND
V	0	0	++	--	0	-	++	0		+	+	ND	ND	ND	-	ND	ND	ND	-	+	ND	ND	ND	0	ND
Y	0	0	++	-	0	-	0	0	+		-	--	ND	ND	-	ND	ND	--	-	+	ND	+	++	0	0
B	ND	-	-	-	0	+	0	-	+	-		ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Cl	ND	+	+	ND	ND	ND	ND	ND	ND	--	ND		ND	ND	ND	ND	ND	ND	++	++	ND	ND	+	ND	0
Eu	++	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND		ND	ND	+	++	++	ND	ND	+	+	ND	ND	++
Hf	++	ND	++	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND		ND	+	++	++	ND	ND	+	+	ND	ND	++
Li	0	0	-	0	ND	+	-	++	-	-	ND	ND	ND	ND		ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Pb	0	ND	+	ND	ND	ND	ND	ND	ND	ND	ND	ND	+	+	ND		0	0	ND	0	ND	0	ND	ND	+
Mo	++	ND	0	ND	ND	ND	ND	ND	ND	ND	ND	ND	++	++	ND	0		++	ND	ND	ND	+	ND	ND	+
Nb	++	++	++	ND	ND	ND	ND	ND	ND	--	ND	++	++	++	ND	0	++		++	ND	+	++	ND	ND	0
Rb	++	+	0	-	ND	ND	-	-	-	-	ND	++	ND	ND	ND	ND	ND	++		ND	ND	ND	ND	-	0
Si	+	0	+	-	0	0	+	-	+	+	ND	ND	ND	ND	ND	0	ND	ND	ND		ND	ND	+	ND	ND
Th	+	ND	+	ND	ND	ND	ND	ND	ND	ND	ND	+	ND	ND	ND	ND	ND	+	ND	ND		+	ND	ND	+
U	0	+	++	0	ND	ND	ND	ND	ND	+	ND	+	+	ND	ND	0	+	++	ND	ND	+		ND	ND	+
Yb	+	+	+	-	ND	+	ND	ND	ND	++	ND	ND	ND	ND	ND	ND	ND	ND	ND	+	ND	ND	ND	ND	ND
Zn	0	+	0	0	ND	0	0	0	0	0	ND	ND	ND	ND	ND	ND	ND	ND	-	ND	ND	ND	ND	ND	ND
S	+	+	+	ND	ND	ND	ND	ND	ND	0	0	++	++	ND	ND	+	+	0	0	ND	+	+	ND	ND	ND

TABLE B7
Ridge Basalt Correlation Matrix: Major Elements

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1		+	-	0	0	0	-	0	-	0	0	0	0	-	0
2 SiO ₂	+		0	0	0	0	0	+	0	0	0	0	-	0	-
3 Al ₂ O ₃	-	0		--	--	-	++	0	0	0	-	-	0	--	0
4 TiO ₂	0	0	--		++	0	--	0	0	0	++	++	+	++	0
5 Total iron as Fe ₂ O ₃	0	0	--	++		0	--	0	0	0	+	++	0	++	0
6 MgO	0	0	-	0	0		0	0	0	0	0	-	0	0	-
7 CaO	-	0	++	--	--	0		-	0	0	0	-	-	0	--
8 NaO	0	+	0	0	0	0	-		0	0	0	0	0	0	0
9 K ₂ O	-	0	0	0	0	0	0	0		0	0	0	0	0	0
10 H ₂ O	0	0	0	0	0	0	0	0	0		0	0	+	0	+
11 MnO	0	0	-	++	+	0	0	0	0	0		+	0	+	0
12 P ₂ O ₅	0	0	-	++	++	-	-	0	0	0	+		0	+	0
13 Fe ₂ O ₃	0	-	0	+	0	0	-	0	0	+	0	0		0	++
14 FeO	+	0	--	++	++	0	0	0	0	0	+	+	0		-
15 Fe ₂ O ₃ /FeO	0	-	0	0	0	-	--	0	0	+	0	0	++	-	

TABLE B8
Ridge Basalt Correlation Matrix: Major Elements Versus Trace Elements

	Ba	Sr	Zr	Cr	Co	Cu	Ga	Ni	V	Y	B	Cl	Eu	Hf	Li	Pb	Mo	Nb	Rb	Sc	Th	U	Yb	Zn	S
Water depth	0	0	+	--	+	+	0	+	0	++	ND	ND	-	ND	++	+	ND	ND	--	--	ND	ND	0	+	ND
SiO ₂	+	0	0	--	0	++	++	0	++	+	ND	ND	-	ND	0	-	ND	ND	0	0	ND	ND	0	0	ND
Al ₂ O ₃	-	0	--	+	--	-	-	0	--	--	ND	0	-	ND	-	++	ND	-	0	--	ND	ND	--	--	ND
TiO ₃	0	0	++	0	0	0	0	0	0	++	ND	ND	+	ND	+	++	ND	0	0	0	ND	ND	++	++	ND
Total iron as Fe ₂ O ₃	0	0	++	0	0	0	+	0	++	++	ND	0	+	0	+	-	ND	ND	0	++	ND	ND	++	++	ND
MaO	++	-	0	0	+	0	++	++	+	+	ND	ND	0	ND	0	--	ND	ND	+	+		ND	0	0	ND
CaO	0	0	--	0	-	0	0	0	-	--	ND	ND	0	ND	-	0	ND	0	0	-	ND	ND	--	--	ND
	0	+	++	0	0	0	0	0	0	++	ND	ND	-	ND	++	0	ND	ND	0	0	ND	ND	+	+	ND
K ₂ O	++	0	+	0	++	+	++	+	++	++	ND	0	0	ND	++	-	ND	0	++	0	ND	ND	+	+	ND
H ₂ O	--	+	0	0	0	0	-	-	-	+	ND	ND	+	ND	+	++	ND	0	++	0	ND	ND	+	+	ND
MnO	--	0	+	0	0	0	-	0	0	++	ND	ND	ND	ND	0	++	ND	ND	-	0	ND	ND	+	+	ND
P ₂ O ₅	0	+	++	0	0	0	0	--	0	++	ND	ND	ND	ND	0	ND	ND	ND	-	0	ND	ND	++	+	ND
Fe ₂ O ₃	--	+	+	0	0	0	0	-	-	0	ND	ND	ND	ND	++	++	ND	0	ND	0	ND	ND	++	+	ND
FeO	+	0	++	0	+	0	+	0	++	++	ND	ND	ND	ND	+	--	ND	ND	ND	++	ND	ND	++	++	ND
Fe ₂ O ₃ /FeO	--	++	0	0	0	-	-	--	--	0	ND	ND	ND	ND	++	++	ND	ND	ND	-	ND	ND	0	0	ND

TABLE B9
Ridge Basalt Correlation Matrix: Trace Elements

	Ba	Sr	Zr	Cr	Co	Cu	Ga	Ni	V	Y	B	Cl	Eu	Hf	Li	Pb	Mo	Nb	Rb	Sc	Th	U	Yb	Zn	S
Ba		-	0	0	0	0	++	++	++	0	ND	ND	ND	ND	-	-	ND	ND	++	++	ND	ND	0	0	ND
Sr	-		0	-	-	0	0	0	+	++	ND	ND	ND	ND	0	+	ND	ND	0	0	ND	ND	0	0	ND
Zr	0	0		-	+	0	0	0	+	++	ND	ND	ND	ND	++	0	ND	ND	0	++	ND	ND	++	++	ND
Cr	0	-	-		0	-	0	0	-	-	ND	ND	ND	ND	--	0	ND	+	+	-	ND	ND	--	0	ND
Co	0	-	+	0		+	+	++	0	0	ND	ND	ND	ND	++	++	ND	ND	ND	++	ND	ND	++	+	ND
Cu	0	0	0	-	+		++	+	0	+	ND	ND	ND	ND	++	++	ND	+	ND	++	ND	ND	++	+	ND
Ga	++	0	0	0	+	++		++	++	++	ND	ND	ND	ND	++	-	ND	ND	+	+	ND	ND	+	0	ND
Ni	++	0	0	0	++	+	++		+	-	ND	ND	-	ND	0	--	ND	+	0	++	ND	ND	-	-	ND
V	++	+	+	-	0	0	++	+		++	ND	ND	ND	ND	0	--	ND	ND	ND	++	ND	ND	++	+	ND
Y	0	++	++	-	0	+	++	-	++		ND	ND	ND	ND	++	ND	ND	ND	ND	++	ND	ND	++	++	ND
B	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND		ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Cl	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND		ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Eu	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND		ND	ND	ND	ND	ND	ND	ND	ND	ND	++	ND	ND
Hf	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND		ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Li	-	0	++	--	++	++	++	0	0	++	ND	ND	ND	ND		ND	ND	ND	ND	ND	ND	ND	+	++	ND
Pb	-	+	0	0	++	++	-	--	--	ND	ND	ND	ND	ND	ND		ND	ND	ND	-	ND	ND	ND	++	ND
Mo	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND		ND	ND	ND	ND	ND	ND	ND	ND
Nb	ND	ND	ND	0	+	ND	+	ND	+	ND	ND	ND	ND	ND	ND	ND	ND		ND	ND	ND	ND	ND	ND	ND
Rb	++	0	0	+	ND	ND	+	0	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND		ND	ND	ND	0	ND	ND
Sc	++	0	++	-	++	++	+	++	++	++	ND	ND	ND	ND	0	ND	ND	ND	ND		ND	ND	0	+	ND
Th	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND		ND	ND	ND	ND
U	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND		ND	ND	ND
Yb	0	0	++	--	++	++	++	-	++	++	ND	ND	++	ND	+	ND	ND	ND	0	0	ND	ND		++	ND
Zn	0	0	++	0	+	+	0	-	+	++	ND	ND	ND	ND	++	++	ND	ND	ND	+	ND	ND	++		ND
S	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	